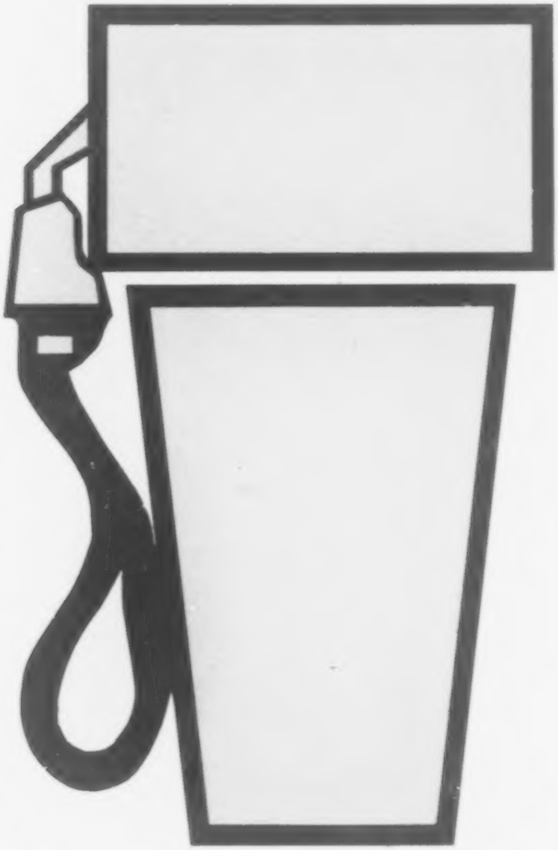
Improving Automobile Fuel Economy

NEW STANDARDS, NEW APPROACHES



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Foreword

Congress is again engaged in a vigorous debate about the future of U.S. energy policy. Key issues in this debate are the ongoing problem of rising oil imports and their effect on national security, balance of payments, emerging concerns about global climate change, and concerns about the health and competitive stance of American industry.

A major policy option in the debate, raising the efficiency of the U.S. automobile fleet by increasing new car fuel economy standards, intersects all three key issues:

- *Oil imports and national security.* Automobiles consume about one quarter of all oil consumed by the U.S. economy; light-duty vehicles (autos plus light trucks) account for nearly four tenths of all U.S. oil consumption.
- *Global warming.* The U.S. light-duty fleet accounts for about 63 percent of U.S. transport emissions of CO_2 and about 21 percent of total U.S. fossil F-fuel CO_2 emissions. Thus, the fleet is an obvious target for global warming mitigation programs.
- *Competitiveness.* Automobile sales and total expenditures represent an important part of the U.S. economy, with new car sales representing about 2 percent of the gross national product (GNP) and total auto expenditures about 10 percent of GNP.

A variety of fuel economy bills and amendments have been introduced, ranging from Senate Energy and Natural Resource's S. 341, which leaves standard setting to the Secretary of Transportation, to H.R. 446, which requires a 60-percent improvement in corporate average fuel economies by the 2001 model year. In weighing the various proposals, Congress must grapple with several crucial issues, all controversial:

- Are regulations the wisest course for saving transportation energy?
- What levels of fuel economy are technically and economically feasible, by what dates?
- What form of standard will deliver high levels of fleet fuel economy with the least market distortion?
- What types of safety impacts might be expected if high fuel economy levels are demanded, and what measures would minimize any adverse impacts?

Inherent in all these issues is the need to sustain the health of the U.S. automotive industry.

This OTA report responds to a request by the Senate Committee on Energy and Natural Resources to examine the fuel economy potential of the U.S. fleet and to assist Congress in establishing new fuel economy standards. In responding to this request, we addressed all but the first of the issues listed above: we have *not* tried to determine whether new fuel economy standards would be inferior or superior to other means to improve fleet fuel economy or, in a broader context, to reduce oil use in highway passenger travel. We recognize that a full examination of all options open to Congress should include the examination of a variety of conservation options including gasoline taxes, traffic control plans, gas guzzler/gas sipper taxes and rebates, improvement of competing mass transportation systems, and so forth. OTA expects to address these and other options in a future study on transportation energy conservation.

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Chapter 1
Executive Summary

BACKGROUND

In the nearly two decades since the first oil shock in 1973, both regulatory pressure (the Energy Policy and Conservation Act of 1975 and its new-car fuel economy standards) and market forces drove fuel economy of the U.S. new car fleet from 14 miles per gallon (mpg) to 28 mpg,[1] saving about 2 million barrels per day (mmbd) of oil that *would have been used* had fuel economy remained at 1975 levels at today's level of driving.[2] Although gradual retirement of older, less efficient cars and their replacement with new ones continue to raise overall efficiency of the fleet, new car fuel economy has plateaued, and overall fleet efficiency will also plateau unless new car fuel economy once again begins to rise. Because demand for auto travel continues to grow, gasoline use must also increase if fleet efficiency stagnates.

Although there is no current shortage of oil and world reserve levels are high, the prospect of rising gasoline demand is profoundly disturbing to national policymakers. The United States has just concluded a war that it was brought into, at least in part, by its own and its allies' dependence on Middle Eastern oil. Falling U.S. oil production and gradually rising demand will expose our economy to greater risks. Further, even without supply disruptions, increased gasoline demand means an ever rising pressure on our balance of payments: purchase of foreign oil now represents the major component of our large international trade deficit. Finally, continued high levels of gasoline consumption help perpetuate the United States' massive emissions of carbon dioxide, the primary "greenhouse" gas, at a time when the nations of the world are pledging to cut back on greenhouse emissions.

Congress has responded to trends in gasoline demand and auto fuel economy by introducing legislative proposals designed to boost fuel economy of the U.S. fleet, primarily by setting new and more stringent standards for Corporate Average Fuel Economies (CAFE) of automakers selling into U.S. markets. Senator Richard Bryan's bill (S.279), calling for a 20-percent improvement in each company's new car fleet average (over a 1988 baseline) by 1996* and 40 percent by 2001 (yielding overall averages of 34 and 40 mpg, respectively), was one of the first of the 102d Congress, but other bills introduced offer different standards and approaches. S.279 and the other bills have generated substantial controversy: the key issue (aside from the obvious question of whether *any* new fuel economy standard is a sensible national policy) is what increase in fuel economy is technically and economically feasible. The relative merit of alternative regulatory *structures*—e.g., level standard, uniform percentage increase, standards based on vehicle interior volumes, and so forth—represents an important issue as well.

This report, requested by the Senate Energy and Natural Resources Committee, examines the major issues associated with developing new fuel economy standards. It builds on work that OTA conducted for its recently delivered report, *Energy Technology Choices: Shaping Our Future*, requested by the House Energy and Commerce

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[1] As measured in EPA laboratory tests using the EPA test cycle and assuming 55 percent city/45 percent highway split. According to EPA, actual on-road values are likely to be about 15 percent less than these test values. Unless stated otherwise, all fuel economy values in this report are EPA values.

[2] $\frac{\text{1975 fuel use}}{\text{1975 VMT}} \times \text{1988 VMT} = \frac{\text{4.54 mmbd}}{\text{1.03 trillion miles}} \times \text{1.43 trillion miles}$

= 6.28 mmbd versus 4.24 mmbd actual 1988 automobile oil use. Data from Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 11*, ORNL6649. NOTE: Had new car fuel economy *actually* remained at the 1975 level of 15.8 mpg, the level of driving might not have grown as much as it did, and the real fuel savings would have been less than calculated here.

*In this report, references to particular years in the context of new car fuel economy goals or levels of attainment denote model years, not calendar years.

Committee and its Subcommittee on Energy and Power. The Energy and Natural Resources Committee's request asked us to focus on the 10- to 15-year timeframe defined by current legislative initiatives for increased automobile fuel economy; in light of this short timeframe, our analysis of fuel economy potential accepts the general concept of the automobile and light truck loosely defined by the types and performance of vehicles in today's fleet. We note that this focus leaves out the potential to rethink the nature of our personal transportation system and to possibly design an altered system of significantly higher fuel efficiency. OTA has considered this strategy of changing the nature of personal transportation in the United States in our 1986 report on *Technology in the American Economic Transition*. In addition, we will revisit the long-term question of U.S. transportation energy efficiency in an ongoing assessment, *U.S. Energy Efficiency: Past Trends and Future Opportunities*.

TRENDS IN FUEL ECONOMY AND USE

Energy analysts agree that without significant changes in market conditions or government policy, increases in the fuel efficiency of the U.S. new car fleet will not match the pace of the late seventies and early eighties. Most improvements during the next decade will come from diffusion of technologies already introduced into the new car fleet; and much of the potential fuel economy benefit may be foregone in order to improve performance (most efficiency technologies can be used instead to improve acceleration or to raise top speeds).[3]

These trends stem from the lack of strong market pressures for improved fuel economy. In the United States, unlike most other industrial countries, fuel cost is a smaller part of total automobile operating expense than previously: gasoline prices in inflation-adjusted dollars are at early 1970s levels, and, when improved fuel economy is accounted for, fuel cost per mile is at its lowest point. Surveys have documented[4] that most consumers are not demanding higher fuel economy in vehicles they purchase.

There are other signs that the market is not supporting reduced gasoline use:

- consumers have been turning in growing numbers to less efficient light trucks for passenger vehicles: between 1970 and 1985, light-truck miles tripled while auto miles grew by only 38 percent;
- automakers are building, and consumers are buying, increasingly powerful cars: average 0-to-60 mph acceleration times of the U.S. auto fleet have decreased in every year since 1982, at a cost of more than 2 mpg in average fuel economy;
- consumers increasingly order options that reduce fuel efficiency, such as air-conditioning, power accessories, and fourwheel drive;
- new emission and safety standards are likely to have an adverse effect on fuel economy; and
- the growing number of autos creates traffic congestion that lowers on-road efficiency of the fleet.

OTA estimates that a continuation of current trends—which is likely if public policies do not change and oil prices remain stable (and low)—will lead to a 1995 U.S. new car fleet fuel economy of about 29 mpg. If oil prices increase later in the decade[5] and automotive engineers seek optimum fuel economy benefits from technologies they install, we project a rise in new-car fuel economy to 33 mpg in 2001; lower prices or less-than-optimal designs could lead to fuel economy levels well below this value.

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[3] By failing to reduce engine displacement or increase axle ratios to compensate for reduced loads or increased engine output, instead using the increased power/load ratio to improve performance.

[4] J.D. Powers has documented fuel economy's drop from first to eighth place over the period 1980-87 as a factor U.S. consumers consider in selecting a new car.

[5] Gasoline price assumed to be about $1.50/gallon (1991$) in 2001.

Modest increases in new-car fuel economy, and the implied slower rate of increase in *total fleet* fuel economy, are particularly worrisome because greater demand for highway passenger travel is expected to continue, though at a slower rate than in the past. This does not bode well for attempts to reduce highway fuel use.

Except during brief slowdowns due to oil price shocks and gasoline supply problems, highway travel demand has grown at a remarkably stable rate—about 3 percent per year. Many recent projections indicate much lower growth rates—between 1.5 and 2.0 percent per year. These expectations are based on a slowdown in the growth of women in the workforce, primarily because of approaching saturation; the passing of the baby boom; and possible saturation of annual mileage among adults (employed adult males between 25 and 54 years of age already spend an average of 1.5 hours per day in their cars).

In OTA's view, these projections appear reasonable but not robust—we believe growth rates for highway travel demand could range between 1 and 3 percent, and possibly below 1 percent if gasoline costs were to escalate rapidly or gasoline supply to become a problem. If the projections prove correct, however, U.S. gasoline use would still continue to rise, even if new-car fuel economy follows our more optimistic projections (29 and 33 mpg in 1995 and 2001, respectively); for this case, though, the rate of growth in gasoline use would be only about 0.3 percent per year. This leveling in fuel use would roughly match U.S. experience of the past decade and a half (but with different causes). Between 1973 and 1987, petroleum consumption of the light-duty fleet increased only 7.6 percent—an increase of about 0.5 percent/year—though this occurred while travel demand increased much faster than it is expected to in the future.

Evaluations of likely future trends in travel demand and fuel use must recognize that the demand for travel responds inversely to changes in travel costs—if variable costs decline, travel demand will increase. A consequence of this relationship is that improvements in fleet fuel economy—which will reduce "per mile" fuel costs—will promote some extra driving. Although there is no consensus on the magnitude of this "rebound" effect, policymakers should expect fuel savings from improved fuel economy to be reduced by perhaps 10 or 20 percent from the savings that would occur had the amount of driving been unaffected.

HOW CAN AUTOMOBILE FUEL ECONOMY BE IMPROVED?

An automobile's fuel use is controlled by two factors: the loads on it created by its use; and the efficiency with which it transforms fuel into the work needed to overcome the loads. The loads are the inertial load (when accelerating and climbing grades), air resistance, and the rolling resistance of the tires. Although the magnitude of the loads is partly dependent on the way the car is driven and the terrain, lowering a vehicle's weight, smoothing its shape, and reducing tire rolling resistance will reduce the loads on the vehicle and its fuel consumption. Improving efficiency involves reducing friction in the drivetrain; reducing auxiliary loads with improved air-conditioning, more efficient power steering, etc.; reducing pumping losses, that is, energy needed to pump air and fuel into the cylinder and push out the products of combustion; and so forth. Although modern automobiles have achieved substantial sophistication and efficiency, numerous opportunities to improve fuel economy remain. Table 1-1 lists key technologies and design improvements that will do so.

Aside from improving technology, materials, and design, fuel economy can be raised by making an automobile smaller in interior space (with an associated decrease in total size and weight) or less powerful. Most current proposals for higher fuel economy standards are predicated on the belief that the standards can be attained *without* major changes in vehicle size and power, though most or all presume that recent trends toward higher horsepower cannot be allowed to continue.

Table 1-1—Fuel Economy Technologies and Design Improvements

Weight reduction. Includes three strategies: substitution of lighter weight materials (e.g., aluminum or plastic for steel); improvement of packaging efficiency, i.e., redesign of drivetrain or interior space to eliminate wasted space; and technological change that eliminates the need for certain types of equipment or reduces the size of equipment.

Aerodynamic drag reduction. Primarily involves reducing the drag coefficient by smoothing out the basic shape of the vehicle, raking the windshield, eliminating unnecessary protrusions, controlling airflow under the vehicle (and smoothing out the underside), reducing frontal area, etc.

Front wheel drive. Shifting from rear to front wheel drive, which allows: mounting engines transversely, reducing the length of the engine compartment; eliminating the transmission tunnel, which provides important packaging efficiency gains in the passenger compartment; and eliminating the weight of the propeller shaft and rear differential and drive axle. Now in wide use.

Overhead cam engines. OHC engines are more efficient than their predecessor pushrod (overhead valve, OHV) engines through their lower weight, higher output per unit displacement, lower engine friction, and improved placement of intake and exhaust ports.

Four valve per cylinder engines. Adding two extra valves to each cylinder improves an engine's ability to feed air and fuel to the cylinder and discharge exhaust, increasing horsepower/unit displacement. Higher fuel economy is achieved by downsizing the engine; the greater valve area also reduces pumping losses, and the more compact combustion chamber geometry and central spark plug location allows an increase in compression ratio.

Intake valve control. Shift from fixed-interval intake valve opening and closing to variable timing based on engine operating conditions, to yield improved air and fuel feed into cylinders and reduced pumping loss at low engine loads.

Torque converter lockup. Lockup eliminates the losses due to slippage in the fluid coupling between engine and transmission.

Accessory improvements. Adding a two-speed accessory drive to more closely match engine output to accessory power requirements, plus design improvements for power steering pump, alternator, and water pump.

Four- and five-speed automatic transmissions, and continuously variable transmissions. Adding extra gears to an automatic transmission increases fuel economy because engine efficiency drops off when its operating speed moves away from its optimum point, and the added gears allow the transmission to keep the engine closer to optimal speed.

Electronic transmission control. Electronic controls to measure vehicle and engine speed and other operating conditions allow the transmission to optimize gear selection and timing, keeping the engine closer to optimal conditions for either fuel economy or power than is possible with hydraulic controls.

Throttle body and multipoint fuel injection. Fuel injection allows improved control of the air/fuel mixture and thus allows the engine to continually adjust this mixture for changing engine conditions. Multipoint also reduces fuel distribution problems. In wide use.

Roller cam followers. Most current valve lift mechanisms are designed to slide along the camshaft; shifting to a rolling mechanism reduces friction losses.

Low friction pistons/rings. Lower friction losses result from better manufacturing control of tolerances, reduced ring tension, improved piston skirt design.

Improved tires and lubricants. Continuation of longstanding trends towards improved oil (in near-term, substitution of 5W-30 oil for 10W-40 oil), and tires with lower rolling resistance.

Advanced engine friction reduction. Includes use of lightweight reciprocating components (titanium or ceramic valves, composite connecting rods, aluminum lifters, composite fiber reinforced magnesium pistons), improved manufacturing tolerances to allow better fit of moving parts, available post-1995.

Electric power steering. Used only for cars in the minicompact, subcompact, and compact classes.

Lean burn. Operating lean improves an engine's thermodynamic efficiency and decreases pumping losses. Requires a new generation of catalysts that can reduce NO_x in a "lean" environment.

Two-stroke engines. Unlike a conventional engine, there is a power stroke for every ascent and descent of the piston, thus offering a significantly higher output per unit of engine displacement, reduced pumping loss, smooth operation, and high torque at low speeds, allowing engine downsizing and fewer cylinders (reduced friction losses). Also, operates very lean, with substantial efficiency benefits (if NO_x problems are solved). Compliance with stringent emissions standards is unproven.

Diesel engines. Compression-ignition engines, or diesels, are a proven technology and are significantly more efficient than gasoline two-valve engines even at constant performance; new direct injection turbocharged diesels offer a large fuel savings. Although the baseline gasoline engine will improve in the future, a portion of the improvements, especially engine friction reduction, may be used beneficially with diesels as well. Use may be strongly limited by emissions regulations and consumer reluctance.

Electric hybrids. Involves combining a small electric motor for city driving and a diesel for added power and battery charging. The small size of the diesel eases emission limitations, and the substantial use of the electric motors reduces oil use.

SOURCE: Office of Technology Assessment, 1991

However, a significant *reduction* in average vehicle size and performance could offer a substantial benefit in increased fuel economy; and measures to change consumer preferences (especially economic incentives such as gasoline taxes and rebates on high fuel economy vehicles) might be attractive components of a fuel conservation strategy.

To be successful, however, a fuel economy strategy featuring smaller, less powerful cars requires far more change in consumer attitudes than one based on technological changes only; the latter affects primarily a vehicle's price and, in the case of improved aerodynamics, its aesthetics, whereas the former can strongly affect a vehicle's basic utility, comfort, and driving enjoyment.

Fuel economy improvement strategies that rely heavily on changing consumer preferences for more size and power or limiting consumers' choice of vehicles risk consumer disappointment in new car offerings, reduced sales, and a reduced fleet turnover rate—with turnover being a critical factor in improving overall fleet fuel economy and, of course, in maintaining the financial health of the auto industry. Consequently, legislators who believe fuel economy standards should be raised substantially need to identify a fuel economy level and regulatory program design that balances dual goals of pushing hard for improved vehicle technology and design and maintaining a new car fleet that remains attractive to potential purchasers. They should also carefully consider the advisability of economic incentives, such as gasoline taxes, vehicle rebates, and taxes tied to fuel economy, that would tend to align market forces with regulatory requirements.

WHAT IS THE FUEL ECONOMY POTENTIAL OF THE U.S. NEW CAR FLEET?

Congress has been bombarded with a wide range of estimates of the "technological potential" of the fleet. Many differences among these estimates result not from actual differences in technical judgment about the efficiency improvement of specific technologies, though such differences clearly exist, but instead from differences in assumptions about:

- the timeframe of the higher fuel economy levels, thus the lead time available to the industry to make technical and marketing changes;
- the nature of regulations accomplishing the efficiency change;
- future shifts in the size mix of the fleet;
- changes in acceleration capabilities or other measures of vehicle performance;
- passage of new safety and emission regulations;
- time required to develop, perfect, certify, and bring to market new technologies;
- judgments about acceptable levels of economic disruption to the industry in responding to new fuel economy regulations; and
- judgments about consumer response to changes in vehicle costs and capabilities (which are, in turn, a function of oil prices and supply expectations).

These factors must be considered in calculating "technological potential," since each will affect the ultimate fuel economy achieved by the fleet.

OTA has examined estimates of technological fuel economy potential ranging from conservative estimates prepared by domestic automakers to optimistic estimates prepared by energy conservation advocates. The range of views about fuel economy potential can be characterized as follows: At the conservative extreme, further increases in fleet fuel economy are characterized as likely to be quite small, even by 2001, because the major gains have already been achieved, consumer tastes are heading towards vehicle characteristics that conflict with higher fuel economy, and government safety and emissions standards will tend to degrade fuel economy.[6] At the optimistic extreme, large increases in fleet fuel economy, to 45 mpg and higher, are portrayed as readily obtainable by existing or soon-to-be-available technology, possibly as early as the year 2000.

As explained in the text, OTA concludes that estimates prepared by Energy & Environmental Analysis, Inc. (EEA), under contract to OTA and the Department of Energy, provide the best available basis for decisionmaking about fuel economy policy. We note that the EEA analyses must be used in context: each individual estimate of fuel economy potential for a "scenario" of particular circumstances is associated with a set of critical assumptions that determines the magnitude of reported fuel economy values. In some regards, EEA estimates may be somewhat conservative for the 2001 timeframe, because they do not consider the possibility that new technologies, not yet commercially available, may begin penetrating the market by that date, nor do they consider the potential for diesel engines to overcome their current negative market perceptions and their problems in meeting emission requirements. On the other hand, the available EEA scenarios all assume that, *at the worst*, vehicle performance, use of luxury equipment, and size will not increase indefinitely but instead level off after 1995; other scenarios assume a policy-driven rollback in these characteristics to 1990 or 1987 fleet levels. These assumptions could prove too optimistic.

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[6] Quantitative industry mpg estimates are not identified here because the automakers have been reluctant to provide estimates in this form.

Table 1-2 provides OTA's estimates for a variety of fuel economy scenarios, ranging from a "product plan" projecting likely fleet fuel economy in a "business as usual" scenario (no new fuel economy regulations, no major shifts in market factors), to a "maximum technology" scenario estimating what could be achieved if regulations forced maximum use of fuel economy technologies and accelerated model retirement rates, to a longer term projection postulating the success of several new technologies such as two-stroke en-

Table 1-2—Scenarios of Automotive Fuel Economy

		Fuel Economy Levels Achieved[1]
1995	• Product Plan cost-effective technology, continuation of current trends, no new policy initiatives	28.3 mpg domestic[2] 31.1 mpg imports 29.2 mpg fleet
	• Regulatory Pressure fuel economy potential with added pressure of new efficiency regulations, but without size/class shifts	30.0 mpg fleet
2001	• Product Plan at Rising Oil Price no new policy initiatives and no radical changes in market, but higher oil prices ($1.50/gal gasoline in 1991$); size/performance/luxury stable after 1995, tier 2 emissions standards not considered	32.0 mpg domestic 34.6 mpg imports 32.9 mpg fleet
	• Maximum Current Technology feasible technology added regardless of cost, size/performance/luxury rolled back to 1987 levels, normal lifecycle requirements not allowed to limit technology penetration rates, no advanced technologies	37.3 mpg domestic 39.9 mpg imports 38.2 mpg fleet
	• Regulatory Pressure technology added that is cost-effective at $2.00/gal. gasoline (higher than expected price levels), 10-year payback, size/performance/luxury rolled back to 1990 levels, technology penetration limited by normal lifecycle requirements, no advanced technologies	34.5 mpg domestic 37.4 mpg imports 35.5 mpg fleet
2005	• Regulatory Pressure as above	36.5 mpg domestic 38.4 mpg imports 37.1 mpg fleet (38.1 mpg w/2-stroke)
2010	• Advanced Technologies size/performance/luxury rolled back to 1987 levels, no new emissions standards post-2000	
	– addition of technologies that most automotive engineers agree would be commercialized by 2000	45 mpg fleet
	– addition of technologies not having general agreement about benefits and commercial prospects.	55 mpg fleet

[1] EPA tests cycle, combined city/highway; potential credits for alternative fuel vehicles NOT considered.

[2] "Domestic" refers to vehicles made and sold in the United States by the three U.S. automakers; imports refers to vehicles sold in the United States by the top five Japanese automakers.

SOURCE: Office of Technology Assessment, 1991, based on analysis by Energy & Environmental Analysis, Inc., 1991.

gines. The "regulatory pressure" results illustrate one example of a set of scenarios that may be viewed by some as a "middle-of-the-road" strategy, although it does assume a rollback in vehicle size and performance to 1990 levels in defiance of current upward trends, and technology additions that will not be cost-effective at expected gasoline prices.* OTA does not, however, believe that there is any "best" fuel economy strategy.

As illustrated by these scenarios, we find neither extreme of fuel economy potential described—"little change" or 45 mpg plus by 2000—credible for that timeframe. Our analysis shows that the application of multiple existing technologies can increase fleet fuel economy by several mpg, and up to about 10 mpg by 2001 if consumers accept some rollback in vehicle size and performance and are willing to pay more for improvements in fuel economy than they will likely be repaid in fuel savings—but such acceptance is not a foregone conclusion given existing market trends, as discussed. Chapter 4 includes a detailed description of the current market trends affecting fuel economy. More detailed description of the alternative fuel economy scenarios and their underlying assumptions are presented in chapters 7 and 9.

Larger gains, to 45 mpg or even higher, *may* be available by 2010 if new technologies could make major gains in the marketplace, although the success of these technologies is by no means guaranteed. For this, the automakers need time to redesign their model lines and to develop and adequately test new technologies.

As noted, changing consumer preferences for fuel economy, vehicle size, and vehicle performance (or, in the extreme, imposing limits in choice of these attributes) offers an alternative approach to improving new-car fleet fuel economy. Moderate changes in purchaser selection of vehicles within size or weight classes toward more efficient models, and shifts in size or weight class to smaller vehicles can substantially increase fleet fuel economy. For example, in the 1990 U.S. new car fleet, had consumers purchased only the dozen most fuel efficient models in each weight class, and shifted their purchases toward lighter weight classes so that average weight was reduced by 6.2 percent, the fleet fuel economy would have improved from 27.8 to 33.2 mpg, a 20 percent improvement. About two-thirds of fuel economy improvement would have been due to consumers selecting the more efficient vehicles in each weight class, with the remainder due to the actual shift in weight class market shares. The "cost" of the improvement (in terms of loss of consumer attributes) would have been a 7-percent decrease in the average interior volume of the fleet (from 107 to 99 cu.ft.), an 11-percent increase in 0-to-60 mph acceleration time (12.1 to 13.4 seconds), and a major shift from automatic to manual transmissions (about 40 percent of the fuel economy benefit would be lost if drivers refused to switch transmission types). The "average car"—the car that attains the average fuel economy of the fleet and is representative of its average characteristics—would have shifted from a Dodge Dynasty to a Toyota Camry.

What, then, should be the targets for a new generation of fuel economy standards? If Congress wishes to set a fleet target for model year 1996 that pushes the industry further than it would otherwise be likely to go, we believe a realistic target would be 30 mpg assuming no significant changes in current trends in vehicle size and performance. With full use of available alternative fuel credits, a *reported* fleet average[7] of 31 mpg should be feasible. The fleet average could be considerably higher than this if consumers changed their buying preferences for efficiency, performance, and size; legislators will have to weigh the benefits of attaining this higher level with the risks, in particular the potential for customer dissatisfaction with smaller, lower-powered cars, resulting lower vehicle sales, and the consequent impacts on the U.S. automobile industry.* Congress could reduce these risks by coupling higher fuel economy standards with economic incentives—gasoline taxes and rebates and penalties tied to fuel economy—designed to push the market towards higher efficiency.

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*The gasoline price that would yield cost-effectiveness ($2.00/gal) was chosen to represent one possible value of the total societal cost of gasoline, that is, actual market price plus costs of air pollution damage, global warming contribution, national security impacts, and so forth. Different policymakers should have different opinions of what an appropriate societal cost might be.

[7] That is, the tested value plus any available credits.

For the longer term, the choice becomes more difficult because there are more options and more uncertainties. The "maximum technology" value of 38 mpg in 2001 assumes a rollback in size and performance to 1987 levels, an increase in vehicle costs that will *not* be offset by fuel savings (unless gasoline prices rise substantially), and the early retirement of several model lines, which could be costly to the industry. The compression of vehicle lifecycles embodied in the maximum technology scenario is not unprecedented, however, and legislators may feel that growing oil imports and the need to reduce greenhouse emissions warrant such measures. Further, a high fuel economy standard may accelerate the entry of new technologies, such as the two-stroke engine, into the fleet—though not without market and technical risks.

For legislators who believe that the market should better reflect societal costs of oil but who wish neither to demand that the industry abandon product lines before their initial costs can be recovered nor to risk requiring major changes in vehicle size and performance, a fleet target of around 35 mpg should be feasible by 2001. Alternatively, a "maximum technology" scenario that assumed a rollback in size and performance only to 1990 levels would yield a fleet average fuel economy of about 37 mpg by 2001. The change in size and performance between 1987 and 1990 cost over one mpg in new-car fleet fuel economy. *Because of the importance of lead time, these potential fuel economy targets presume passage of new fuel economy legislation by the end of calendar year 1991. Substantial delays in promulgating new rules would lower fuel economy values attainable in the target year.*

For the still longer term (2010 and beyond), there is real potential for fleet fuel economy values of 45 mpg or even 55 mpg,[8] but considerable uncertainty as well because of untested technologies. For this time period, Congress might consider mechanisms to insure continued technological pressure while maintaining enough administrative discretion to reduce fuel economy goals if optimistic forecasts of technology potential turn out to be incorrect.

WHICH TYPE OF STANDARD IS BEST?

Recent proposals for new fuel economy legislation have moved away from the format of current law, which imposes a 27.5 mpg standard on all automakers. With the current format, automakers producing a variety of vehicle sizes or primarily large vehicles are subject to a more demanding technological challenge than automakers who concentrate on small vehicles. This gives the latter automakers more flexibility to capture markets for larger cars and to introduce features (high-performance engines, four-wheel drive, etc.) that are both attractive to consumers and fuel inefficient—putting full line and "high end" manufacturers at substantial market disadvantage.

Many legislators would not approve a new fuel economy standard unless domestic automakers could comply without a drastic shift in their fleets toward small cars—but a "uniform mpg" standard set under a restriction of this sort would be unlikely to force automakers making primarily small cars to improve very much. As a result, the maximum fuel economy the fleet could be expected to attain with a uniform mpg format would be lower than with a format that challenges *all* automakers to substantially improve their CAFEs.

New legislative proposals ask that automakers raise their CAFEs by a uniform percentage over

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*New car sales represent about 2 percent of U.S. GNP, and total expenditures for automobile use represent about 10 percent of GNP—illustrating the importance of the automobile industry to the U.S. economy.

[8] Even higher values could be achieved, but only with major changes in the basic character of the cars, e.g. with large numbers of diesel/electric hybrid vehicles.

what they had attained in a baseline year—1988 in Senator Bryan's proposal (S. 279); 1990 in S. 1220, reported by the Senate Energy Committee. Because the 1988 or 1990 CAFEs reflect in some measure the size makeup of each company's fleet, their use as a baseline for assigning fuel economy requirements will account for the differences in size among the various companies—but only to the extent that these differences do not change from the baseline year to the compliance year. If companies seek to gain share in market segments different from their traditional market (e.g., by marketing large luxury cars), the uniform percentage increase approach could prevent them from doing so—and may be viewed as anticompetitive. Furthermore, to the extent that some differences for the baseline year were due to differences in fuel economy technology and design, a uniform percentage increase standard places the most severe new demands on those companies who in the past had tried hardest to improve their fuel economy. There *have* been differences in fuel economy technology and design among the different automakers, and several companies have, through deliberate marketing strategy or through loss of market shares, changed their size mix over time—both factors compromising the internal logic of the uniform percentage increase approach to CAFE regulation.

An alternative approach to fuel economy standards is to base company standards on the attributes of each company's fleet at the time the standards are to be met. If based on interior volume, for example, a new standard would place the highest numerical fuel economy target on the company making vehicles with the lowest interior volumes. Such a Volume Average Fuel Economy (VAFE) standard could be designed to place as equal as possible a technological (or financial) burden on each automaker. This type of standard would put no pressure on automakers to build small (low interior volume) cars[9]—a minus with those conservationists who believe most cars are too large, a plus with others who believe consumers should have an unrestricted choice of car size and who may also believe large cars are safer. Instead, a VAFE standard demands that automakers focus on technology, design, and performance to improve fuel economy, removing the contentious issue of car size from the policy debate. A perceived disadvantage of a VAFE standard is that any increase in market share of cars in the larger size classes could reduce the overall fleet fuel economy target, a potential outcome that disturbs some policymakers; however, a uniform percentage increase standard could also have its total fleet target reduced with market changes.[10]

Another potential problem with VAFE standards—and with the original uniform 27.5 mpg standard—is that they are difficult to apply to manufacturers falling outside the competitive mass market. Companies such as Mercedes-Benz and BMW sell products that stress high performance, luxury, and safety at a high price. Traditionally, their vehicles are substantially heavier than other vehicles in their size class, more powerful, and have rear-wheel drive (to achieve the handling characteristics they seek), all of which compromise fuel economy. These companies cannot match the fuel economies of mass market automakers in their size classes at similar levels of technology.

Basing fuel economy standards on a wider group of vehicle attributes could provide more of a move to a "pure technology" standard, that is, a standard that can be met only by improving technology rather than by reducing size or power. Mercedes-Benz, BMW, and Porsche have proposed a standard based on a group of variables—curb weight, the ratio of curb weight to interior volume, and the ratio of curb weight to torque—that would allow companies in a wide range of market niches to comply with a reasonable standard by improving technology, without being forced to move into other markets to "balance" their production of niche vehicles. The standard is formulated by performing a regression analysis,[11] using EPA data for the 1990 fleet, that defines current vehicle fuel consumption as a function of the above three variables. A standard requiring 1995 fleet fuel economy to be at least 20 percent higher than the 1990 level would simply reduce the 1990-based fuel consumption function by 20 percent and apply this new function to each automaker's fleet. As with the uniform percentage increase and VAFE standards, this system will not guarantee attainment of an exact fuel economy level (because the market can change), but it will force technology improvement and it provides positive incentives for weight and performance reduction.

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[9] Because smaller cars will have higher fuel economy targets, and selling more of them will not make it easier for an automaker to achieve its company standard—unless the size-based targets are deliberately set to give smaller cars a less difficult target fuel economy than large cars would have.

[10] For example, if an automaker with a relatively low mpg target gained market share, the overall fleet fuel economy target would be reduced.

WHAT IS THE BEST SCHEDULE FOR NEW STANDARDS?

Legislation proposed during last year's (1990) debate focused on setting new fuel economy standards for the (model) years 1995 and 2000. This year, these dates have been changed to 1996 and 2001 to reflect the loss of a year of lead time for the automakers. Are these the best years for a set of new standards?

Generally, the design and product development lead time for new models and major components is about 4 to 5 years, indicating that products for the 1996 model year are now being finalized, while products for 1995 have moved to a stage where tooling orders are being placed. Models of domestic automakers will have a lifecycle of at least 7 to 8 years prior to redesign, during which their large development costs must be recovered. Japanese models tend to have shorter lifecycles, as short as 4 years.[12]

These time horizons imply, first, that 1996 is very early to demand significant improvements in fuel economy beyond that already built into product plans, and second, that 2001, while allowing enough time for major adjustments to be made, is early for a standard that might seek fleetwide redesign *unless Congress believes energy concerns warrant a redesign schedule that would induce accelerated retirement on several model lines.* Although OTA has reached no conclusion about what an optimal schedule might be, a set of dates that would allow an interim fuel economy adjustment followed by a full redesign of all model lines *without forced early retirements* would be 1998 and 2004 or 2005. A 2001 standard could also be included, predicated on redesign of only a portion of company model lines.

NEW FUEL ECONOMY STANDARDS AND SAFETY

Industry and Administration opposition to new fuel economy standards has included arguments that higher standards, such as those proposed by S.279, would force consumers into a new fleet of smaller cars significantly less safe than a new fleet with an unchanged size mix—and perhaps even less safe than the current fleet.[13] In OTA's view, unless sharp fuel economy improvements are demanded over a period too short to allow vehicle redesign, or the fuel economy requirements are so stringent they can only be met with drastic levels of downsizing, it is unlikely that *absolute* levels of safety would decrease. The continued introduction of new safety improvements, and wider use of already introduced improvements should compensate for adverse effects of moderate amounts of downsizing. Further, if given enough time, automakers can significantly improve fleet fuel economy *without* downsizing (though with some weight reduction), and probably without an adverse safety impact. Nonetheless, there *is* cause for concern about the relationship between fuel economy and safety, and there is reasonable probability that further downsizing—especially a reduction in exterior dimensions—would cause the fleet to be less safe than it would otherwise be. However, we also find that the debate about the relationship between fuel economy and safety has at times become overheated,[14] and assertions on both sides of the debate seeking to demonstrate the magnitude of risk are frequently flawed or misleading.

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[11] A regression analysis involves a statistical examination of data that seeks to determine functional relationships among variables that the analyst believes to be related, for example, between fuel economy and weight and horsepower (variables that should affect fuel economy).

[12] Light trucks may have somewhat longer lifecycles.

[13] For example, see statement of Jerry Ralph Curry, Administrator, National Highway Traffic Safety Administration, before the Subcommittee on Energy and Power, House Committee on Energy and Commerce, Oct. 1, 1990.

Car size can be characterized by weight, interior volume, or exterior dimensions. Each has a different relationship to safety. Added weight may help the heavier car in a vehicle-to-vehicle collision, because the laws of momentum dictate that a heavier car will experience less deceleration force in a crash—but the weight and safety advantage afforded the first car represents a disadvantage to the second car, increasing the force on it. Although accident records have demonstrated a *statistical* relationship between *overall* fleet safety and average weight of the vehicles in the fleet, the strong association between weight and various measures of vehicle size, especially exterior dimensions, makes it difficult to separate effects of weight and size. Many safety experts think size is more important than weight to overall fleet safety, even though weight may be important to consumers making individual purchase decisions. If carmakers can make vehicles lighter while retaining structural integrity—and with proper materials, they can—there should be no adverse safety impact.

Interior volume may affect safety somewhat because a larger interior makes it easier for vehicle designers to manage the "second crash"—when bodies are flung about the passenger compartment. The average interior volume of the U.S. automobile fleet has been remarkably stable over the past decade, but there is concern this may change if fuel economy standards are set at levels that cannot be attained with technology alone. However, increased airbag use may make differences in interior space less important to overall vehicle crashworthiness, because airbags should reduce movement—and likelihood of secondary collisions—of front-seat passengers in a crash.

Exterior dimensions may be particularly important to a car's crashworthiness, since these affect available crush space, and narrower vehicle tracks and shorter wheelbases appear to affect rollover frequency (rollover accidents are often associated with fatalities). Accident studies have shown that some of the largest vehicles in the fleet consistently have the lowest fatality rates, even when the data are corrected for driver characteristics (especially age). Further, studies by the National Highway Traffic Safety Administration indicate that small vehicles experience more rollover accidents, and more traffic fatalities in such accidents than large vehicles, and the Insurance Institute for Highway Safety claims downsizing has driven up death rates in several redesigned General Motors models.

Will new fuel economy standards decrease automobile safety? It depends, and we believe the risks are less than those characterized by some. First, substantial increases in fuel economy can be achieved with little or no downsizing, although automakers might conceivably choose downsizing over other measures to satisfy new fuel economy standards. Although vehicle *weight* would likely be reduced, this need not have negative safety consequences if careful attention is paid to vehicle structural integrity.

Second, even if further downsizing were to decrease safety relative to not changing standards, this need not mean, and probably would not mean, an *absolute* safety decrease. During the period when CAFE standards have been in effect, when the median weight of new automobiles dropped by about 1,000 pounds, wheelbase by 10 inches, and track width by 2 to 3 inches, the safety record of the U.S. fleet improved substantially—between 1975 and 1989, death rates for passenger cars *declined* from 2.43 per 10,000 registered cars (2.5 per 100 million miles) to 1.75 per 10,000 registered cars (1.7 per 100 million miles).[15] In other words, *at worst* reductions in vehicle size and weight reduced somewhat the fleet's overall improvement in safety during this period, and new standards might well do the same. Not surprisingly, this outcome can be interpreted in radically different ways: by proponents of more stringent standards as indicating that better fuel economy was achieved without compromising safety, in fact with substantially improved safety, and that this can be the case in the future; and by opponents as indicating that nearly two thousand lives per year that *could have been saved* were not, because of forced downsizing of the fleet,[16] and that, similarly, new standards will reduce our ability to improve the safety record in the future. Both viewpoints may be valid.

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[14] The rhetoric has ranged from asserting that safety and vehicle size are essentially unrelated to suggesting that S.279 be referred to as "The Highway Fatality Bill."

Third, all differences in safety between small and large cars do not seem irrevocable, as stated by some officials, but instead may be amenable to correction. Safety technologies now entering the fleet, including airbags and antilock brakes, will work at least as well on small cars as on large ones, and will tend to decrease any safety "gap," measured in fatalities per 100 million miles, between the two. Also, some safety features may focus on problems specific to small cars. A major cause of fatalities in small cars appears to be a high propensity of these cars to roll over, as noted. OTA believes that design improvements should be available to ameliorate this problem and further reduce the safety gap between large and small vehicles.

Fourth, in determining the likely safety outcome of further fleet downsizing, it may be incorrect to assume that all safety features incorporated into a downsized fleet would have been incorporated had no downsizing occurred. Under this assumption, new safety features don't really compensate for downsizing, since even more lives could be saved with the same features added to a fleet of larger vehicles. In the past, however, government rulemaking, consumer pressure, and automaker design decisions did not occur in isolation from changes in the actual safety situation. They occurred in response to perceived safety problems, not to some absolute safety standard. In other words, had the problems been less severe, fewer safety measures may have been taken. To the extent that future safety responses would be driven by problems emerging from future downsizing, the argument that safety would have been still greater without the downsizing may become, at least in part, disingenuous.

Opportunities to counteract any adverse impacts of new fuel economy standards may be prevented by lack of resources. According to the Transportation Research Board, Federal funding for highway safety research has been cut 40 percent since 1981—to only $35 million per year—despite the enormous cost in dollars and tragedy ($70 billion, 45,000 deaths, 4 million injuries per year) of traffic accidents. Additions to safety research and development resources could go a long way toward mitigating any negative consequences of future fleet downsizing.

We conclude that potential safety effects of fuel economy regulation will most likely be a concern if increases in fleet fuel economy are required over a period too short to allow substantial vehicle redesign—forcing manufacturers to try to sell a higher percentage of small cars of current design. In our view, significant improvements in fuel economy should be possible over the longer term—by 2001, for example—without compromising safety. Over this time period, there are opportunities to improve fuel economy without downsizing, as well as opportunities to redesign smaller cars to avoid some safety problems particular to them. However, the *potential* for safety problems will still exist, if automakers emphasize downsizing over technological options for achieving higher fuel economy and if they do not focus on solving problems such as increased rollover propensity in small cars of current design. If auto fatality rates would be lower without new fuel economy standards than with them—even if overall rates decline—then a real tradeoff between new standards and safety *does* exist and must be addressed explicitly during the fuel economy debate.

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[15] National Highway Traffic Safety Administration, "Fatal Accident Reporting System 1989," draft, table 1-2B. For all motor vehicles, death rates declined from 3.23 per 10,000 vehicles (3.4 per 100 million miles) to 2.38 per 10,000 vehicles (2.2 per 100 million vehicles), table 1-1.

[16] NHTSA, "The Effect of Car Size on Fatality and Injury Risk."

FUEL SAVINGS FROM S. 279

The magnitude of fuel savings likely from a new fuel economy standard is both a critical component of the decision calculus for the policy debate about standards and a source of great controversy because of large differences in estimates prepared by opposing interests. The source of these differences is the set of assumptions associated with each estimate. Critical assumptions affecting the magnitude of estimated savings include:

1. *Fuel economy values without new standards.* Alternative assumptions about the fuel economy of the new car fleet *in the absence of new standards* will play a critical role in estimating fuel savings associated with new standards. Factors affecting future fleet fuel economy include future oil prices and price expectations, fuel availability, consumer preferences for vehicle size and power, new safety and emissions standards, and progress in technology development. The span of credible assumptions about future fuel economy is likely to be quite wide, especially for the late 1990s and beyond.
2. *Use of alternative fuel credits.* Manufacturers can claim up to 1.2 mpg in CAFE credits by producing vehicles capable of using alternative fuels. Depending on whether automakers would produce large numbers of alternative fuel vehicles if there are no new fuel economy standards—both the Clean Air Act and new California emission standards provide incentives to do so—the actual fuel savings associated with new standards could be reduced.
3. *Magnitude of a "rebound" in driving.* An increase in fuel economy, by reducing "per mile" costs, may stimulate more driving and thus reduce the associated fuel savings. The magnitude of a "rebound" effect is controversial, with estimates ranging up to 30 percent of potential fuel savings lost to increased driving.
4. *Magnitude of vmt growth.* Small differences in the growth rate of vehicle miles traveled (vmt) can make a significant difference in the fuel savings estimated to occur from a new standard. In OTA's view, the credible range of future rates is fairly broad, perhaps from 1 percent per year to 3 percent per year, which translates into a variance of 1.3 mmbd in estimated fuel savings for S. 279 in the year 2010.
5. *Effects of new standards on vehicle sales.* Some opponents of new fuel economy standards have argued that stringent standards will have the effect of slowing vehicle sales (because of higher vehicle prices and reduced customer satisfaction with smaller, slower, less luxurious cars), reducing vehicle turnover and the positive effect this has on fleet fuel economy. Others consider the likelihood of a sales slowdown large enough to affect fleet fuel economy in a significant manner to be very small. Clearly, an effect on turnover is theoretically possible, and would be likely if policymakers were to miscalculate and set a standard beyond automakers' technical capabilities.

Different estimates of the likely fuel savings from S.279, which requires 20 percent (by 1996) and 40 percent (by 2001) improvements in each automakers fleet fuel economy levels, include:

- American Council for an Energy-Efficient Economy (ACEEE), for the Senate Commerce Committee: 2.5 mmbd by 2005.
- Department of Energy: 0.5 mmbd in 2001, 1 mmbd by 2010.
- Congressional Budget Office: 0.88 mmbd by 2006 and 1.21 mmbd by 2010 (base case); range of 0.45 to 1.42 mmbd by 2006 and 0.59 to 1.82 mmbd by 2010.

The differences among the above estimates can be readily understood by examining their assumptions. For example, ACEEE assumes that fuel economy levels will remain unchanged from today's in the absence of new standards, i.e., about 28.5 mpg for cars and about 21 mpg for light trucks. The Department of Energy has assumed that, without new standards, new vehicle fleet fuel economy will rise to about 33 mpg for cars and 24 mpg for light trucks by 2001, and remain at that level thereafter. CBO has chosen baseline mpg values of 30 mpg (range 28.5 to 33.0 mpg) for 2001. This difference in baseline mpg assumptions is the most important factor in accounting for differences among the estimates.

Similarly, DOE has chosen assumptions about alternative fuel credits, rebound effect, and vmt growth rate that will tend to yield lower estimated fuel savings than ACEEE, with CBO choosing assumptions somewhat in between. Much of the difference stems from DOE's assumptions of rising oil prices—$29/barrel (1990$) in 2000 and $39/barrel (1990$) in 2010.

OTA concludes that the DOE baseline estimate of 1 mmbd fuel savings from S.279 by 2010 is analytically correct but very conservative. Although none of its assumptions are extreme, virtually *all* push the final result towards a low value. In our view, the likelihood of such uniformity is small, although much less improbable if oil prices follow their assumed (upwards) path.

In contrast to the DOE estimate, the Bryan/ACEEE estimate of 2.5 mmbd by 2005 appears very optimistic because it discounts the potential for a driving "rebound" and, more importantly, accepts unusually pessimistic assumptions about likely fuel economy improvements in the absence of new standards.

Although the range of potential fuel savings from S. 279 is wide, OTA believes that the "most likely" value for year 2010 savings lies between 1.5 and 2 mmbd. For a 10 percent rebound effect, 2 percent/year vmt growth rate, baseline fuel economy of 32.9 mpg in 2001 (frozen for the next decade), and no accounting for alternative fuel vehicles, we calculate the fuel savings to be 1.64 mmbd in 2010. Although the 32.9 mpg baseline (no new standards) value is optimistic unless oil prices rise substantially, it is also likely that the automakers will gain some alternative fuel credits in the baseline; these two factors will tend to cancel one another.

Figure 1-1 displays the projected U.S. oil consumption over time with and without enactment of S.279. The figure also displays the consumption projected under OTA's "regulatory pressure" scenario.

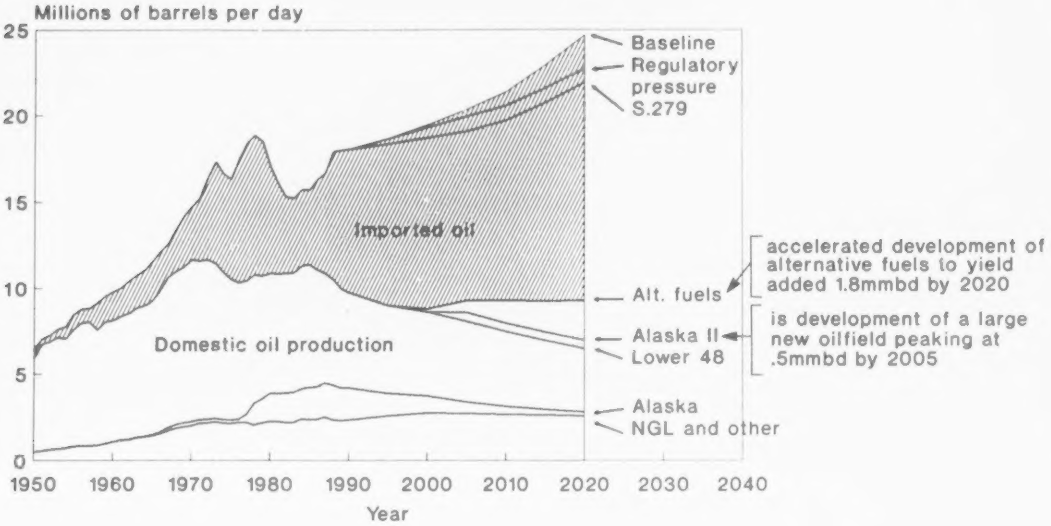
REGULATION OF LIGHT-TRUCK FUEL ECONOMY

Because light trucks make up a rapidly growing proportion of the passenger vehicle fleet, and consumers can readily find transportation alternatives to new cars in the light-duty truck fleet, fuel economy regulations must consider light trucks to assure an effective reduction in total fuel use. Proposed legislation generally recognizes this necessity and sets fuel economy standards for trucks similar to those for automobiles. For example, S.279 proposes that light trucks attain the same 20- and 40-percent fuel economy increases (by 1996 and 2001, respectively) as automobiles.

OTA concludes that currently available technology will not allow automakers to improve light-truck fuel economy to the same extent as they can improve passenger automobiles *unless* diesels become more popular in the 6,000- to 8,500-pound category of light trucks. Sources of fuel economy limitations include:

- load carrying requirements that impose structural and power needs that are more a function of payload weight than body weight of the truck—yielding fewer flow-through benefits from initial weight reduction;
- open cargo beds for pickups and large ground clearance that limit potential for aerodynamic improvements;
- need for low end torque, limiting benefits from four-valve engines; and

Figure 1-1—U.S. Oil Consumption Under Alternate Scenarios—With or Without Higher Fuel Economy Standards



ASSUMPTIONS
1 Baseline assumes no new policy measures, new car fuel economy reaches 32.9 mpg in 2001 and stays constant thereafter.
2. S. 279 assumes new car fuel economy reaches 40 mpg by 2001 and 50 mpg by 2020.
3 Regulatory pressure assumes new car fuel economy reaches 35 mpg by 2001 and 45 mpg by 2020.

SOURCE: Office of Technology Assessment, 1991.

- likelihood of additional safety and emission requirements, with associated fuel economy penalties.

The use of all available technologies (except diesels in the smaller weight classes) regardless of cost could allow light-truck fleet fuel economy to improve from about 20 mpg to about 26 mpg by 2001.

A "uniform percentage increase" approach to regulating light-truck fuel economy is particularly problematic because of extreme differences in truck fleet composition among different automakers. A format based on truck attributes, similar in concept but not in details to automobile standards based on interior volume, might be preferable. Such standards would have to be individually tailored to truck types—undoubtedly an opportunity for considerable argument about which type each particular model falls into. As a point of departure for further study, appropriate standards might look as follows:

- ***passenger vans***—standards based on interior volume, probably measured somewhat differently than for automobiles;
- ***utility vehicles***—standards based on passenger interior volume, with an mpg credit for rough-terrain capability; and
- ***pickup trucks and cargo vans***—standards based on both volume and tonnage[17] of load carrying capacity (e.g., square or cubic foot-tons).

Given the growing importance of light trucks to overall fuel consumption, more attention needs to be paid to the problems associated with regulating these vehicles.

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[17] **We note, however, that measures of load carrying capacity would have to be carefully developed and monitored to avoid manipulation.**

Chapter 2

Introduction

The purpose of this report is to assist Congress in evaluating and, if desired, revising a series of legislative initiatives establishing new fuel economy standards for new automobiles sold in the U.S. market. As indicated by the congressional committee requesting this report, the time frame of these initiatives is the coming decade, and OTA's evaluation focuses on this time period—although we do examine, in lesser detail and certainly with less precision, some longer range potential. As a result, we examine the technological potential for improved automotive fuel economy primarily in terms of vehicles similar in type and performance to vehicles in today's fleet. Although we do examine the impact of a shift in consumer tastes towards the smaller and more efficient models in this fleet, we have not examined the potential to design vehicles that are radical departures from today's with different performance, size, and function from vehicles we are familiar with, nor have we tried to rethink the basic nature of our personal transportation system. Both of these are important dimensions of the future of the Nation's transportation that should not be overlooked. OTA will examine these dimensions in an ongoing assessment, *U.S. Energy Efficiency: Past Trends and Future Opportunities*.

Strategies to reduce fuel use by the U.S. fleet of light-duty highway passenger vehicles—automobiles and light trucks—are at the focal point of debate concerning several important issues affecting the United States. In particular, problems associated with an unstable oil supply and national security, a large trade imbalance aggravated by rising oil imports, and the potential for global warming primarily due to burning of fossil fuels all contribute to congressional interest in reducing light-duty vehicular fuel use. Although a variety of policy measures can address this goal, new automobile fuel economy standards have been at the center of congressional debate. A brief discussion of the national energy security and global warming issues appears in box 2-A.

Trends in U.S. oil consumption, production, and imports have worsened over the past few years, adding to long-standing concerns about U.S. energy security, balance of trade, and environmental quality (see figure 2-1). In 1985, the United States was enjoying substantial success in reining in oil consumption, maintaining domestic production, and thus reducing imports. In that year, we produced nearly 9 million barrels per day (mmbd) of crude oil and 11.4 mmbd of total liquid fuels;[1] consumed 15.7 mmbd, down from 18.4 mmbd in 1977; and imported 4.3 mmbd, only 27 percent of total supply, down from a 1977 high of 8.6 mmbd or 46 percent. At the end of 1985, however, world crude oil prices plunged, drastically reducing incentives for production investments and easing economic restrictions on consumption. Since 1985, domestic crude oil production has fallen well below 8 mmbd; total petroleum consumption has risen back over 17 mmbd; and net oil and product imports have grown to over 7 mmbd in 1990, close to 45 percent of total consumption, and are still rising.[2] In fact, most major forecasts of U.S. energy supply and demand project that, *without major changes in energy policy*, oil imports will exceed 50 percent of total oil[3] consumption within a few years. **OTA's previous**

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[1] That is, crude oil, lease condensate, natural gas plant liquids, processing gains, alcohols, and other liquids.

[2] U.S. Department of Energy, Energy Information Administration, *Short-term Energy Outlook, 2nd Quarter 1990*, DOE/EIA-0202(90/2Q). NOTE: Figures for oil import percentage vary with the source, and some public figures are quoting values well above 50 percent for the U.S. oil import level. These values almost certainly are based on inappropriate comparisons of total product and crude oil imports to domestic crude oil production without accounting for domestic production of natural gas liquids, which are a valuable part of our total petroleum supply.

[3] That is, all liquid fuels, including crude oil, lease condensates, natural gas plant liquids, processing gain, alcohols, etc. Most statements of import dependence refer to imported crude oil and petroleum products as a fraction or percentage of total liquid fuels consumption.

Box 2-A—The U.S. Light-Duty Fleet, Energy Security, and Global Warming

Efforts to update past fuel economy regulations and boost substantially the efficiency of the U.S. light-duty fleet of automobiles and light trucks are based primarily on two key policy issues facing the United States: the perceived insecurity of U.S. oil supplies and the growing threat of global warming from rising atmospheric concentrations of carbon dioxide and other so-called "greenhouse" gases.

Energy Security. After a decade of quiescence, energy security has once again become a major U.S. concern. The key statistic driving that concern is the level of U.S. oil imports, which had dropped to 27 percent of supply by 1985 but rose to 42 percent in 1989,[1] and continues to rise steadily as U.S. oil production drops. As in the 1970's, four basic elements underlie the concern: the near-total dependence of the U.S. transportation sector on petroleum; the United States' limited potential to increase oil production; the preponderance of oil reserves in the Middle East/Persian Gulf area; and the basic political instability and considerable hostility to the United States existing there.

In fact, in some ways these elements have grown more severe since the energy crises of the seventies. During the past 10 years (1979-89), the transportation sector's share of total U.S. petroleum use has grown from 53 to 63 percent as transportation has remained almost totally oil-dependent while other sectors have switched to alternate fuels.[2] This is particularly important because the sector's prospect for switching fuel in an emergency is virtually zero. In addition, the boom-and-bust oil price cycle of the post-boycott period, and especially the price drop of 1985-86, may have created a wariness in the oil industry that would substantially delay any major boost in drilling activity in response to another price surge. And, with the passage of time, the industry's infrastructure, including skilled labor, needed for a drilling rebound is being eroded

Despite these problems, OTA believes that, on balance, the United States' energy security is somewhat less at risk today than in the 1970's. Shifts in the oil market that we consider as supporting increased energy security include:

- the Strategic Petroleum Reserve and increased levels of strategic storage in Europe and Japan;
- increased diversification of world oil production since the seventies;
- the end of U.S. price controls, allowing quicker market adjustment to price and supply swings;
- advent of the spot market and futures market, making oil trade more flexible;
- increasing interdependence of the world economy, particularly the major investments of OPEC producers in the economies of the Western oil-importing nations and, especially, in their oil-refining and marketing sectors;
- lessening of the strategic importance of the Gulf of Hormuz due to diversification of transport routes out of the Gulf;
- growing importance of natural gas, and its substitutability for oil in key markets; and
- recent political changes in Eastern Bloc nations and the resulting lowering of tensions between East and West.

Iraq's rising military power and recent invasion of Kuwait threatened this trend toward improved security by concentrating control of much of the world's oil resources in one country. The successful war effort liberated Kuwait and seriously weakened Iraq's military capability; but it may also have far-reaching repercussions on power balances, alliances, and attitudes toward the United States and the West. Whatever the outcome, the likelihood of continuing tensions in the Gulf and the considerable enmity

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[1] U.S. Department of Energy, Energy Information Administration, *EIA Monthly Energy Review*, DOE/EIA-0035(91/01) January 1991, p. 13; cited hereafter as "*MER* 1/91." NOTE: "Oil" refers to all crude oil, natural gas liquids, and oil products.

[2] *MER* 1/91, pp. 7,27.

Continued on next page

toward the United States there will create a strong incentive to reduce U.S. dependence on imported oil. In fact, even with the positive outcome in the war, the U.S. effort and the refugee problems created still have the potential to yield new animosities towards the United States that would have negative implications for long-term energy security.

Global Warming. The need to slow and reverse the growth of worldwide emissions of carbon dioxide (CO_2) and other greenhouse gases has provided new impetus to energy conservation measures.

The greenhouse effect is a warming of the Earth and atmosphere resulting from trapping of the Earth's outgoing infrared radiation by CO_2, water vapor, methane, nitrous oxide, chlorofluorocarbons, and other gases, both natural and manmade. Although there are respected scientists who remain skeptical that significant greenhouse warming will occur, most scientists believe that growing atmospheric concentrations of the greenhouse gases caused by past and ongoing increases in emissions rates will lead to significant global temperature increases: a widely accepted value is a global average temperature increase of 3 to 8°F. (1.5 to 4.5°C.) from a doubling of CO_2 concentrations or the equivalent.[3] Other effects of the warming include an expected rise in sea level, drastic changes in rainfall patterns and increased incidence and severity of storms, and resulting disruptive impacts on agriculture and natural biological systems.

Despite substantial scientific consensus about the likely change in average global temperatures, there is also substantial disagreement and uncertainty associated with regional impacts, effects of various temperature feedback mechanisms such as clouds, the role of the ocean, the relative greenhouse effect of the various gases, and other factors. These uncertainties affect arguments about both the urgency and value of conservation measures such as improving automobile fuel economy.

The U.S. light-duty fleet accounts for about 63 percent of U.S. transport emissions of CO_2, 3 percent of world CO_2 emissions, and about 1.5 percent of the total greenhouse problem. This last value has been variously interpreted as being a significant percentage of the greenhouse problem, and as proving that focusing on the U.S. fleet to gain consequential greenhouse benefits is a mistake. In OTA's view, few if any sectors of the U.S. economy are large enough, *by themselves*, to significantly alter the course of greenhouse warming. In other words, ignoring the light-duty fleet as "too small a factor" is identical to deciding to do nothing. An effective strategy to mitigate greenhouse warming must address all sectors of the economy. Furthermore, the global nature of the automobile and light-truck market and the economic importance of the U.S. market imply that acceleration of improvements to the fuel economy of the U.S. fleet can have a strong ripple effect on the fuel economy of the worldwide fleet.

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[3] Other gases have a warming effect that is some multiple of [the effect of] CO_2; so a combination of increases of various gases can be translated into an effective CO_2 increase by appropriately weighting the increased concentration of each gas.

review of domestic oil production prospects[4] and its preliminary review of oil demand generally support these projections.

If trends in imports are to be changed, improved efficiency of use is widely expected to be at the head of the list of policy options. During the decade and a half since the first oil price shock, the major factor in reducing U.S. oil imports was the marked reduction in the energy intensity of the U.S. economy, attributable at least in part to dramatic increases in the efficiency of energy use. Many opportunities remain to continue this downward trend in energy intensity.

Because of its importance to U.S. petroleum use, the transportation sector is a main target for further efficiency efforts. In 1988, this sector accounted for approximately 27 percent of total energy consumed by the United States[5] and, more

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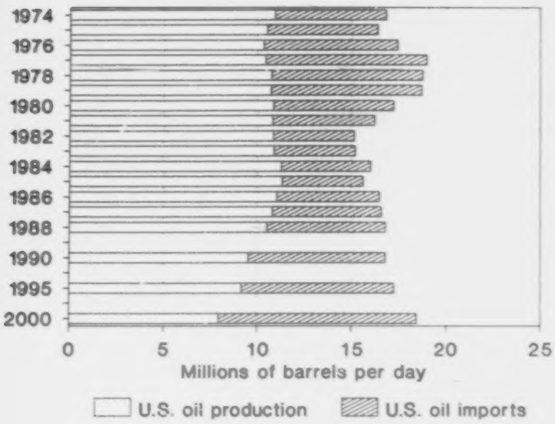
[4] U.S. Congress, Office of Technology Assessment, *U.S. Oil Production: The Effect of Low Oil Prices-Special Report*, OTA-E-348 (Washington, DC: U.S. Government Printing Office, September 1987).

[5] *MER* 1/91, p. 21.

Figure 2-1—U.S. Oil Balance



SOURCE: Energy Information Administration, *Annual Energy Outlook 1991*

importantly, 63 percent of all U.S. petroleum consumption.[6] Furthermore, a substantial portion of the remaining oil use involves consumption of byproducts of refinery production of transportation fuels.[7] Reducing the use of these byproducts would not have a major impact on overall oil supplies unless transportation fuel use were reduced as well.

The light-duty highway fleet—automobiles and light trucks (vans and pickups) used largely for passenger travel—accounts for a very large portion of U.S. transportation energy use and overall oil use. In 1988, this fleet accounted for 38.2 percent of U.S. oil consumption and 15.7 percent of total energy consumption. The automobile fleet alone was responsible for about 26.2 percent of U.S. oil consumption and 10.8 percent of total energy consumption.[8] Consequently, **the automobile and light truck fleets represent the largest available targets for reducing U.S. petroleum use, and they have in fact become the focal points of recent efforts to involve the Federal Government more actively in energy efficiency efforts.**

This report addresses a *part* of what the Federal Government can do to reduce fuel usage by the light-duty highway fleet; it focuses solely on enacting fuel economy regulations governing the efficiency of the fleet. The full range of options open to the Government is much broader, and includes strategies to:

- *reduce light-duty vehicle travel demand* by improving other travel modes, reducing the need for travel (e.g., by better urban planning or promotion of video conferencing), or increasing the costs of using light-duty vehicles;
- *reduce congestion*;
- *reduce maximum highway speeds*;
- *increase vehicle occupancy*; and
- *improve vehicle efficiency* through technology and design and through changes in the tradeoffs automakers *and consumers* make between fuel economy and other vehicle attributes such as performance and interior space.

The government can influence the efficiency of the fleet by accelerating fleet turnover; increasing gasoline costs (e.g., by a gasoline tax increase); taxing inefficient vehicles or giving rebates on efficient ones; and regulating new-car fuel economy.

Congress enacted the initial Corporate Average Fuel Economy (CAFE) regulations 15 years ago (see box 2-B). Although there appears a widespread public consensus that the CAFE program was a substantial success—in the interim period, average fuel economy of new cars improved by

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[6] *MER* 1/91, pp. 7, 27.

[7] Data from U.S. Department of Energy, Energy Information Administration, *1989 Annual Energy Outlook*, DOE/EIA-0383(89), January 1989.

[8] Data from Oak Ridge National Laboratory, *Transportation Energy Data Book, Edition 11*, ORNL-6649, January 1991; and Energy Information Administration, *Annual Energy Review 1988*, DOE/EIA-0384(88), May 1989. Different sources of data and different definitions will give somewhat different values. For example, light trucks may include all light trucks, as in table 2.8 in the Oak Ridge document, or light trucks used for personal passenger travel, as in table 2.13 of the same document. For the value shown here, we use total light trucks, primarily because we don't have good data over time for the breakdown of personal light truck travel and freight light truck travel. Otherwise, using the lower figure for personal travel, as in table 2.13, would be preferable. Furthermore, the value for total energy consumption varies with data source. We use 83.4 quads for 1988, from the Energy Information Administration.

Box 2B—Corporate Average Fuel Economy (CAFE) Standards and Measures

In 1974, world oil prices tripled and the fuel economy of the new U.S. passenger car fleet hit a low point of 14 mpg. Congress responded to these events by passing the Energy Policy and Conservation Act of 1975 (Public Law-163), which established CAFE standards for each automaker, starting at 18 mpg in 1978 and increasing to 27.5 mpg by 1985. Fleet CAFE values are measured as the sales-weighted harmonic mean of the individual fuel economies of an automaker's models, with domestically produced and imported vehicles measured as separate fleets.

The Corporate Average Fuel Economy standards and many fuel economy statistics cited in the literature are expressed as the results of the test procedure administered by the Environmental Protection Agency. These values are not equivalent, even approximately, to actual on-road, or in-use, fuel economy values because EPA dynamometer tests do not fully simulate realworld driving conditions, and because the maintenance of the fleet and the driving behavior of the public may be quite different than that experienced during the tests.

EPA analyses conducted in 1984[1] determined that the new car fleet achieved average on-road fuel economy levels about 10 percent and 22 percent less, respectively, than EPA city and highway tests indicated. Using the 55 percent city/45 percent highway split adopted by EPA to simulate average driving, the composite on-road fuel economy would be about 15 percent less than the EPA composite. EPA uses the adjustment factors to calculate an approximate on-road average for each new car model, for reporting to potential purchasers. Also, most estimates of future automotive fuel usage use the same 15 percent adjustment factor applied to estimated future EPA new car fuel economies to calculate the fuel use of each model year's fleet. Consequently, forecasting fuel use by the highway sector depends substantially on the stability of the 15 percent adjustment factor.

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[1] K.H. Hellman and J.D. Murrell, "Development of Adjustment Factors for the EPA City and Highway MPG Values," Society of Automotive Engineers technical paper SAE 840496, 1984.

100 percent, from about 14 mpg to roughly 28 mpg[9]—there is strong dissension with this view among automakers and in certain academic and business circles. The dissenters claim most efficiency improvements resulted from market demand driven by rising oil prices and price expectations. Some have even claimed the regulations may actually have *reduced* total fleet fuel economy from what it would otherwise have been by slowing vehicle turnover during those periods when oil prices fell and consumers placed a low value on high fuel economy and a high value on those vehicle attributes (performance, vehicle weight) compromised by the need to improve fuel economy. Further, some dissenters claim the regulations, by forcing domestic automakers to increase sales of small cars (generally by lowering prices) and to downsize large cars, degraded overall safety of the fleet.[10] The issue of the relationship among fuel economy regulations, vehicle size, and overall vehicle safety is discussed in chapter 9.

One of the more powerful arguments that CAFE regulations *did* play a major role in improving new car fleet fuel economy is that those automakers that were constrained by the standards (primarily those with full car lines or lines tilted towards larger vehicles) exhibited significantly different behavior than those that were relatively unconstrained (those making primarily subcompacts and compacts). As discussed by

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[9] As measured by the Federal test administered by the Environmental Protection Agency. Actual on-road fuel economy has been lower than the test values by about 15 percent, on average.

[10] For a cogent summary of these arguments, see R.W. Crandall, "The Changing Rationale for Motor Vehicle Fuel-Economy Regulation," *Regulation*, fall 1990.

Greene,[11] constrained automakers moved their fleet fuel economies upwards almost in lockstep with rising CAFE standards, whereas unconstrained automakers did not improve their fleet fuel economies as fast and tended to level off much earlier. Greene's statistical analysis indicates that the standards were at least twice as important as changes in oil prices as a "driver" of fuel economy.

This report does not attempt to resolve these two points of view; we are not certain any quantiitative analysis would prove sufficiently convincing to end the argument. We note, however, that the process of enacting new fuel economy regulations balances important societal and private benefits (lower emissions of carbon dioxide, reductions in oil imports, lower fuel bills) against societal and personal costs (market distortions, potential losses in vehicle safety, increased capital expenditures for car design and manufacture, higher new car prices). At the "right" level, new fuel economy standards should save substantial quantities of oil, though at a cost. On the other hand, there may be some level beyond which further increases in the standards would be damaging to the industry: the standards would raise vehicle prices or degrade vehicle size and performance enough to significantly reduce new car sales. Because retirement of old, inefficient cars and their replacement with new efficient cars are the primary forces driving steady growth in fuel economy of the total on-road automobile fleet, slower turnover caused by overly stringent standards theoretically could produce a net *increase* in fuel use compared to more lenient standards. At a lesser extreme, even standards that would save large quantities of oil may have costs that outweigh their benefits; few if any policymakers believe oil savings should be pursued regardless of cost. Members of Congress who favor new fuel economy standards must take care to set standards that are a reasonable compromise between the need to encourage more fuel efficient design and technology, and a range of competing values.

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[11] D.L. Greene, Oak Ridge National Laboratory, "CAFE OR PRICE? An Analysis of the Effects of Federal Fuel Economy Regulations and Gasoline Price on New Car MPG, 1978-89," contract paper for Office of Policy Integration, U.S. Department of Energy, revised Nov. 30, 1989.

Chapter 3

Where Does Improved Fuel Efficiency Come From?

Automobile fuel economy can be improved by two basically different kinds of measures—reducing the loads on the automobile, thus reducing the work needed to move it; and increasing the efficiency of converting energy contained in the fuel to work. The loads consist of the force needed to accelerate the auto (to overcome inertia), air resistance, and rolling resistance of the tires. The efficiency of conversion is determined by the efficiencies of the drivetrain components—engine, transmission, and axles, and all auxiliaries, including cooling system, alternator, fuel pump, lighting, power steering, and so forth.

In city driving, the three types of loads on the automobile are comparable.[1] In steady, level driving, the inertia load is essentially zero, but most urban driving consists of repeated acceleration and deceleration, making the inertia load high. Because the force needed to accelerate a vehicle is purely a function of weight, weight reduction through improved design, acceptance of less space, or materials substitution is a critical factor in fuel economy, especially for the urban part of the cycle. On the highway, however, air resistance tends to dominate the total load, because resistance increases with the square of velocity—wind resistance at 60 mph is 9 times resistance at 20 mph $[(60/20)^2]$. Thus, reducing the aerodynamic load on the auto by increasing its "slipperiness" (reducing its drag coefficient) or reducing its cross-sectional area will greatly improve highway fuel economy and have a small but important effect on all but very low-speed urban driving.

Aside from reducing the loads, fuel economy can be improved by improving the engine's efficiency in converting fuel chemical energy into mechanical energy delivered to the wheels. The conversion of chemical to heat energy and then to mechanical energy results in an energy loss inversely proportional to combustion temperature (i.e., the higher the temperature, the lower the loss). Current limitations in the ability of materials to function at very high temperatures (as well as emissions regulations, especially for nitrogen oxides) limit combustion temperature to a level that results in a theoretical 70-percent maximum utilization of the total energy available in the fuel. Other practical considerations related to the combustion cycle result in gasoline engines having an efficiency of only 35 to 38 percent at their optimal operating points (i.e., this is their peak efficiency). Since the Federal Test Procedure driving cycle has variable loads and speeds, engines operate well below their peak for significant portions of the test cycle (this is true as well for most normal driving). At idle, for example, engine "efficiency" is zero. On average, over the entire fuel economy test, the engine operating efficiency is about one-half peak efficiency.

The engine average efficiency can be improved by three different methods: increasing thermodynamic efficiency, reducing frictional losses, and reducing pumping losses (pumping losses are the energy needed to pump air and fuel into the cylinder and push out the products of combustion). The first, increasing thermodynamic efficiency, is limited by the characteristics of the spark ignition engine. Increasing the compression ratio increases thermodynamic efficiency; but other parameters related to fuel octane, nitrogen oxide emissions, and friction (emissions and friction increase with increasing compression ratio, and the octane level limits how high the ratio can go without obtaining premature combustion) result in declining benefits as compression ratios increase from today's 9.0 to 10.0 and beyond. Combustion chamber redesign can provide small increases in thermal efficiency. Higher thermodynamic efficiencies can also be achieved with compression ignition (diesel) engines.

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[1] M. Ross, "Energy and Transportation in the United States," *Annual Review of Energy 1989*, vol. 14, pp. 131–171, figure 9.

[2] Energy & Environmental Analysis, Inc., *An Assessment of Potential Passenger Car Fuel Economy Objectives for 2010*, draft final report to the Environmental Protection Agency, Air and Energy Policy Division, February 1991.

Mechanical friction can be reduced by improving design of rubbing and sliding surfaces or using new materials and lubricants. Decreasing the weight of the piston, connecting rod, valves, and valve springs also reduces frictional losses. Replacing sliding contact surfaces with rolling contacts can provide significant benefits in friction reduction. No theoretical limit currently exists for reducing mechanical friction, and historically, engine friction has declined 8 percent per decade.

Pumping losses include losses due to throttling (i.e., restricting air flow to maintain proper air/fuel ratios when the engine must be operated at a fraction of its peak power capability) and losses due to aerodynamic friction. Throttling loss is proportional to the degree of restriction of the airflow (throttle setting); it is zero at wide open throttle. Throttling loss can be reduced by operating the engine at a lower rpm but higher load for a given vehicle speed, or by using "lean burn" combustion (where excess air is not a problem). For example, the diesel engine uses lean burn and is completely unthrottled. Throttling loss can also be reduced by controlling valve lift and timing or by deactivating cylinders at low loads (so the engine essentially becomes smaller and can operate closer to peak capacity).

Aerodynamic (pumping) losses are associated with the air/fuel mixture as it flows through the air cleaner, intake manifold, and valve orifices, as well as the exhaust as it flows through the valves, manifold, muffler, and catalyst. This loss is proportional to the airmass flow and increases at higher loads and speeds. Aerodynamic losses can be reduced by tuned intake manifolds, increased valve area (or increased numbers of valves), tuned exhaust manifolds, and reduced pressure drop in the catalyst and muffler.

Efficiency improvements in the remainder of the drivetrain can be obtained by reducing frictional loss in the gearbox, axle (or transaxle for front-wheel-drive cars), wheel joints, wheel bearings, brakes, and oil seals. Those improvements can be small individually but provide a measurable cumulative benefit. The use of more gears in the transmission, however, improves efficiency by allowing the engine to operate closer to peak efficiency, rather than by reducing drivetrain loss.

Finally, accessory drives can be made more efficient. Most front-wheel-drive cars already use an electric radiator fan which is engaged only when needed. "Smart" alternators that reduce the load when the battery is fully charged, more efficient water pumps, electric power steering, etc. can reduce the accessory loads that currently account for 8 to 12 percent of all fuel consumed over the test cycle.

Some specific technologies available to reduce vehicle loads and reduce losses include the following (fuel economy benefits were estimated by Energy and Environmental Analysis, Inc., EEA, which has been an OTA technical consultant for this study; for some of the technologies, magnitude of the benefits is controversial):

Weight reduction. Reducing vehicle weight without reducing practical space for passengers and cargo involves three strategies—substitution of lighter-weight materials without compromising structural strength (e.g., aluminum or plastic for steel); improvement of packaging efficiency, that is, redesign of drivetrain or interior space to eliminate wasted space; and technological change that eliminates equipment or reduces the size of equipment. The EEA analysis does not isolate weight reduction directly associated with other efficiency changes, for example, reduced engine weight due to the downsizing (decrease in engine displacement) made possible by engine efficiency improvement, but instead counts the weight reduction as part of the overall fuel economy increase associated with the efficiency change. Most weight reduction gains are expected after 1995. The fuel economy gain available from a 10-percent weight reduction is estimated to be 6.6 percent, including the effect of engine downsizing to maintain constant performance. Without downsizing, the fuel economy benefit would be 4.2 percent. Materials substitution could reduce average vehicle weight 9 percent under 1987 levels by 2001, and 18 to 25 percent under 1987 levels by 2010, with additional weight reduction (3 to 8 percent, depending on market class) possible from improved packaging.

Aerodynamic drag reduction. Aerodynamic drag on a car is the product of its frontal area, its drag coefficient, and the square of its speed. The squared velocity factor means that drag increases very rapidly with speed, and aerodynamic drag is the most important power drain at highway speeds. Reducing frontal area is difficult because, with limited exception, this will compromise interior space. Reducing the drag coefficient involves smoothing out the basic shape of the vehicle, raking the windshield, eliminating unnecessary protrusions, controlling airflow under the vehicle (and smoothing out the underside), and designing the rear end to avoid turbulence and to control behavior of the boundary layer (the thin layer of slow-moving air next to the vehicle's outer surface which exerts an important influence on drag). A 10-percent reduction in the drag coefficient will yield about a 2.3-percent fuel economy gain if the axle ratio or top gear ratio is adjusted to match the engine's operating point to the reduced power requirement. For cars redesigned between now and 1995-96, an average drag coefficient might be 0.335, down from 0.375; for cars redesigned between 1996 and 2001, average drag coefficient might be further reduced to 0.30, which is the level of the most streamlined cars in the U.S. fleet today. Further reductions should be feasible by 2010—drag coefficients of 0.23 to 0.24 seem attainable, and coefficients as low as 0.20 are possible.

Front-wheel drive. Shifting from rear- to front-wheel drive provides a number of fuel-saving benefits, including the ability to mount engines transversely, reducing engine compartment length; elimination of the transmission tunnel, which provides important packaging efficiency gains in the passenger compartment; and elimination of the weight of the propeller shaft and rear differential and drive axle. Counterbalancing these benefits, front-wheel drive changes vehicle handling characteristics in ways objectionable to some drivers (though it offers clear advantages in slippery conditions) and compromises trailer-towing capability. There has been controversy about overall fuel economy gain, because some shifts to front-wheel drive have been made at the same time other downsizing measures were taken, and also because some shifts have been accompanied by increases in vehicle size and in power-to-weight ratio. Total fuel savings available from a shift to front-wheel drive are about 10 percent for vehicles replacing 1970's vintage designs (body on frame), and about 5 percent for those where some potential benefits had already been gained through 1980's redesign (unit body). Because current levels of penetration of front-wheel drive are high and because many remaining rear-wheel-drive vehicles occupy market niches that may favor rear-wheel drive, additional gains available are moderate.

Overhead cam engines. Overhead cam (OHC) engines are used in all imported vehicles; only U.S. manufacturers still sell overhead valve (OHV) engines. Older OHV engines produced less than 40 bhp/liter, but more modern OHV engines provide 45 bhp/liter. In contrast, modern OHC engines provide 50 to 55 bhp/liter in non-sports car applications. The higher specific output is due to the low mass of the valve train that makes it easier to open and close the valves, thereby improving breathing efficiency. A modern OHC engine providing equal performance (i.e., smaller displacement) will yield a 3-percent benefit in fuel economy over a modern OHV engine and up to 6 percent over an older OHV engine.

Four-valve-per-cylinder engines. Adding two extra valves to each cylinder improves an engine's ability to feed air and fuel to the cylinder and discharge exhaust. Four-valve engines typically have sharply higher horsepower than two-valve engines of the same displacement, though peak horsepower is reached at much higher engine speeds, and torque (pulling power) at low engine speeds generally is not improved nearly as much. The major fuel economy gain of a four-valve engine is achieved by downsizing the engine, since this can be done without performance loss; the greater valve area also reduces pumping losses, and the more compact combustion chamber geometry and central spark plug location allows an increase in compression ratio. However, engine downsizing cannot be proportional to horsepower gain because of the resulting lack of low end torque. An important area of uncertainty is the extent to which automakers will be willing to use aggressive transmission management to compensate for a four-valve engine's lack of low end torque by rapidly increasing engine speed when power is needed. This would allow more engine downsizing than if the automaker wanted to maintain the driving "feel" of a high torque, "low revving" engine. Available fuel economy gain over a two-valve overhead cam engine with the same number of cylinders is 5 percent; the gain is 8 percent if a four-cylinder engine replaces a two-valve six cylinder engine, or a six replaces an eight. The gain includes the effect of using a compact combustion chamber and increasing compression ratio from 9.0 to 10.0, which by itself is responsible for a 2-percent gain. By 2010, an increase in compression ratio to 11.0 should be possible, yielding an additional 1-percent gain in fuel economy. These benefits do not include the effect of downsizing to the extent where aggressive transmission management would be necessary.

Intake valve control. All engines have traditionally utilized fixed valve timing since a simple, reliable mechanism to vary timing had not been designed until recently. Thus, valve timing has always been a compromise between high rpm power output and low rpm torque. At part load, it is more efficient to close the intake valves early rather than pump air across the throttle. New devices to vary both valve timing and lift have been commercialized, and such systems have provided 5- to 8-percent gain in lowspeed torque and 20-percent gain in specific power. A valve lift and timing control system can provide 6-percent benefit in fuel economy if the engine is downsized to provide equal low-speed performance, although there may be unfavorable synergies with more advanced transmissions that also reduce pumping loss (these transmissions reduce the amount of time that engines operate at inefficient low-load conditions, when intake valve control is most effective). Valve control systems are most easily incorporated into a double overhead cam, four-valve engine.

Torque converter lockup. Current automatic transmissions utilize a hydraulic torque converter, where an impeller pushes fluid past a turbine to transmit engine torque to the wheels. This hydraulic connection is useful at idle and during acceleration, where it can provide torque multiplication. At higher speeds and low acceleration rates, the system is wasteful as there is some "slippage" between the impeller and turbine. A rigid mechanical link, called a lockup, prevents this slippage and provides a 3-percent benefit in fuel economy if employed in all gears except first. The lockup mechanism also transfers more vibration to the driveline, creating some negative response toward its use. Lockup is now widely used, so available gains are limited.

Accessory improvements. Accessories driven by the engine include the airconditioner, water pump, oil pumps, hydraulic power steering pump, alternator, and, in some cases, the radiator fan. Modest benefits are available in the redesign of all those systems to reduce total energy use. For example, a "smart" alternator can be electronically controlled to provide battery charging only when desirable. Power steering pumps are very wasteful at speed, as they are sized for idle, when steering loads are greatest. Most cars already employ electric fans for the radiator which are switched on when necessary, but further improvement is possible if their speed can be varied. Individually, these accessory benefits are very small but together they can provide a 0.5- to 1.0-percent benefit in fuel economy. One possibility is completely eliminating the hydraulic power steering pump and replacing it with electric power steering. This action alone can increase fuel economy by 1 percent. However, the electrical power demand is so large that electric power steering is thought to be impractical for intermediate and large cars.

Four- and five-speed automatic transmission and continuously variable transmissions. A particular power demand can be met by an engine at different operating points since:

power = torque x speed.

At any level of power demand, the highest torque and lowest engine speed combination—up to a certain point—offers the best fuel economy. Adding gears to an automatic transmission allows operation closer to the optimal combination of torque and speed for any given power demand. Theoretically, a continuously variable transmission (CVT) can keep engine speed at optimal rates for all vehicle speeds. Current CVT designs appear practical only for smaller cars, with two-liter engines or smaller, because of limitations on the amount of power that can be transmitted by the flexible belts in the transmission. Average fuel economy improvement in moving from three-speed transmission with lockup to four-speed with lockup is 4.5 percent, with an additional 2.5 percent available from adding a fifth gear, or an additional 3.5 percent available from moving to a CVT.

Electronic transmission control. Most automatic transmissions currently use mechanical controls to shift gears or engage the torque converter lockup. The controls have been highly developed over the years to match the requirements of the test cycle. Electronic controls can offer a minor benefit by shifting gears and engaging the lockup more efficiently, but the fuel economy gain on the cycle is only 0.5 percent. Under real-world conditions, it is expected to provide greater benefits, especially at operating points outside the test cycle envelope.

Throttle body and multipoint fuel injection. Most vehicles already utilize fuel injection systems that have replaced carburetors. Fuel injection systems are of two types: throttle body, that essentially replaces a carburetor with one or two injectors that supply fuel to all cylinders; and multipoint, that utilizes one injector per cylinder metering fuel directly into the intake port. Fuel injection allows more precise control of fuel quantity metered during transient operation (e.g., acceleration or deceleration) and also atomizes fuel more completely. These factors allow less fuel to be used during cold starts and transients and also improve emissions. The throttle body system provides a 3-percent benefit over a carburetor, if adopting the system eliminates the air pump required to meet emission standards. Widespread use limits available fleet gains, however. A multipoint fuel injection system allows the inlet manifold to be tuned to maximize airflow, as no fuel flows through the manifold. The tuned inlet manifold can increase torque by 3 percent. A multipoint fuel injection system allows fuel shutoff during deceleration. The multipoint system also mitigates fuel distribution problems, allowing leaner mixtures during warmup and slightly more aggressive spark timing after warmup. The combination of a multipoint system with a tuned intake manifold and deceleration fuel shutoff provides a 3-percent benefit in fuel economy relative to the throttle body system.

Improved tires and lubricants. Longstanding trends toward slipperier oil and tires with lower rolling resistance will continue. The recently displayed GM prototype electric car, the Impact, has tires with half the rolling resistance of modern radials. The fuel economy benefit of using the best available oils (5W-30 replacing 10W-40) and tires, now in use on about 20 percent of the 1988 fleet, is about 1 percent. Incremental improvements in tires beyond 1995, available to the fleet in 2001, should yield another 0.5-percent gain. Tires like those of the Impact, if they prove practical, would yield additional gains.

Engine friction reduction. Engine friction is predominantly in the pistons/rings, valve train, and crankshaft. On average about 20 percent of potential engine power is lost to friction; this represents one third of total output power. Engine friction reduction in the 1987 to 1995 timeframe will involve reducing piston ring tension, redesigning the piston skirts (or load bearing area), and improving manufacturing methods to reduce cylinder bore distortions. These efforts will provide a 2-percent fuel economy benefit. Roller cam followers reduce valve train friction by replacing the sliding contact between the roller cam and camshaft with a rolling contact, also providing a 2-percent fuel economy benefit. After 1995, friction reduction will involve the use of lightweight valves and springs, reduction in piston and connecting rod mass through the use of fiber-reinforced composite materials, and possibly, use of only two rings rather than three, with a potential 2-percent fuel economy gain by 2001.

"*Reduced performance.*" Reducing a car's performance is not a "technology," but it *is* a viable option for improving fuel economy. If a smaller, less powerful engine is used in a vehicle, fuel economy gains are obtained from both reduced engine weight and lower throttling losses, because the engine must be operated at full throttle for a greater portion of the driving cycle. For example, if a high-performance vehicle has a 0-to-60 mph acceleration time of 8 seconds, increasing this time by 10 percent—0.8 seconds—will increase fuel economy by about 3.5 percent, about 1 mpg for a 28-mpg car. For a family car with a 14-second 0-to-60 time, a similar increase of 10 percent (1.4 seconds) would add 5.5 percent to fuel economy, or over 1.5 mpg.

Lean burn. Current engines with catalytic controls operate under stoichiometric conditions, that is, using air/fuel mixtures with just enough oxygen to burn all the fuel. This operating environment is necessary to allow the current generation of catalytic controls for nitrogen oxides to work properly; they cannot operate in a "lean" environment, one with excess air. Operating lean, however, improves an engine's thermodynamic efficiency and decreases pumping losses, with potential gains in fuel economy of 10 to 12 percent over current two-valve engines, or about 7 to 10 percent over current four-valve engines. Toyota and other companies are working on new catalyst technology to allow high levels of nitrogen oxides control with a lean burn engine. If development of this control technology is successful, advanced lean burn engines might begin to enter the U.S. fleet in the late 1990s. Although lean burn engines are not new and are in use in Europe, development of the necessary nitrogen oxide catalysts is by no means guaranteed, and this technology should be considered speculative.

Two-stroke engines. In conventional four-stroke engines, the piston descends and ascends in the cylinder twice for every spark ignition and combustion: the first descent and ascent for combustion and power, and then forcing out the exhaust gases; and the second for drawing in air and fuel, then compressing the air/fuel mixture. In a two-stroke engine, the piston need descend and ascend only once for each spark ignition, thus offering significantly higher output per unit of engine displacement: 80 to 100 hp/liter compared to about 60 to 65 hp/liter for an advanced overhead cam, four-valve four-stroke engine. The two-stroke also produces high torque at low speeds, in contrast to multi-valve four-stroke engines; this allows engine downsizing corresponding to the difference in horsepower. The higher frequency of power strokes yields smoother operation, so that a three-cylinder two-stroke engine can replace a six-cylinder four-stroke with minimal change in operating quality and substantially reduced friction losses. Finally, an advanced two-stroke engine will use a direct injection system that will run very lean, adding substantial efficiency benefits (though with potential nitrogen oxide problems because of the inability to use conventional reduction catalysts). Somewhat offsetting these sources of increased fuel efficiency are:

- reduced thermal efficiency of the two-stroke cycle;
- power loss due to the supercharger/blower required for forced scavenging of exhaust gases;
- power losses from the high-pressure fuel injection pump; and
- potential increase in piston friction associated with need for a large piston skirt.

The net fuel economy benefit is likely in the range of 12 to 14 percent over a two-valve four-stroke engine, or perhaps only 3 to 4 percent over an advanced version of a four-valve engine with intake valve control, that will be available for the 2001 fleet. However, the two-stroke may be considerably less expensive than these engines. The key to realizing these benefits is to solve the two-stroke's remaining emissions control problems, especially for application to larger cars where the NO_x emission standards can be limiting. A further tightening of NO_x standards if Tier II standards go into effect will further complicate prospects for this engine.

Diesel engines. Diesel engines represent a proven technology available now to improve fuel economy substantially. However, diesels have not been very successful in the U.S. market for reasons that include performance limitations (most diesels have been significantly less powerful than competing gasoline engines), costs, noise, smell, delayed starting, emissions, and reliability problems associated with some domestic models. Although the 1990 Clean Air Act amendments allow diesels to meet a 1.0-g/mi NO_x standard compared to a 0.4-g/mi standard for gasoline (spark ignition) engines,[3] it is questionable whether this degree of leniency would persist if diesels began to take a major share of the new-car market; and in 2004, diesels must meet the 0.4-g/mi standard (or 0.2 g/mi if Tier II standards are applied). Were NO_x catalysts capable of operating in a "lean," oxygen-rich environment developed, diesels could likely meet stringent NO_x standards. According to European manufacturers, diesels are significantly more efficient than gasoline four-valve engines even at constant performance: 15 to 18 percent more for naturally aspirated diesels, 24 to 28 percent more for turbocharged diesels, and 35 to 40 percent more for direct injection turbocharged diesels.[4] And although the baseline gasoline engine will improve, a portion of the improvements, especially engine friction reduction, may be applied beneficially to diesels as well.

Electric hybrid vehicles. Vehicles that combine an electric motor for city driving with an internal combustion engine for added power, when needed, and battery charging may represent a viable fuel economy alternative. In a version designed by Volkswagen, an 8-hp electric motor powers the car at speeds up to 30 mph and a 1.6-liter diesel engine provides more power for highway driving and other purposes. The weight of the extra engine and batteries (nearly 300 pounds) cuts down on acceleration and fuel economy, but the Volkswagen prototype can still deliver nearly 100 mpg of hydrocarbon energy fuel economy, and 60-mpg (total) fuel efficiency.[5] This type of vehicle represents an interesting opportunity because its use of the electric motor during much of the urban cycle may allow the onboard diesel—or a two-stroke engine—to comply with stringent NO_x standards, such as those in California.

A SPECIFIC EXAMPLE OF THE APPLICATION OF FUEL ECONOMY TECHNOLOGY: HONDA'S NEW CIVIC VTEC-E MODEL

Honda Motors recently announced a new engine that combines Honda's variable valve timing and lift control (VTEC) with lean burn. The combination of technology will be available in model year 1992 in a hatchback model called the Civic VTEC-E, as a 49-state model. The Civic VTEC-E will also be available in California; but this model does not use lean burn. Rather, it uses a high EGR (exhaust gas recirculation) rate but maintains the mixture at a stoichiometric air/fuel ratio. California's stringent NO_x emissions standards are met with use of a three-way catalyst. The Civic VTEC-E in both Federal and California versions has performance very similar to the standard Civic, and the VTEC-E engine and standard DX engine are both rated at 92 hp. However, the Civic VTEC-E provides a substantial increase in fuel economy over the DX model.

Detailed EPA test data were not available at the time of this analysis and preliminary data provided by Honda are used instead. The 1992

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[3] Temporarily for cars and light trucks below 3,750 pounds.

[4] Energy and Environmental Analysis, Inc., February 1991, op. cit.

[5] Ibid.

Civic model is somewhat larger and more aerodynamic than the 1991 Civic (for which detailed data are available), but differences are not large, so that a comparison between a 1992 Civic VTEC-E and a 1991 Civic DX is valid. Table 3-1 shows the relevant data. The 49-State Civic VTEC-E has approximately 44-percent better fuel economy than the 1991 DX, with near-equal acceleration performance, while the California model has 34-percent better fuel economy. The lean burn feature accounts for the 10-percent difference in benefit between the California and 49-State model.

This large increase in fuel economy comes not only from the engine but also a range of other technologies, some made possible by the VTEC engine characteristics. Items unrelated to the engine include:

- 5-percent weight reduction due to reduced options;
- improved aerodynamics due to the addition of an air-dam and removal of one external mirror;
- reduced rolling resistance through use of special tires;
- reduced accessory loads from use of a "smart" alternator; and
- use of fuel-efficient lubricants.

Table 3-1—Comparison of the Civic VTEC-E and DX Models

	1991 Civic	1992 Civic
Test weight (lb)	2,500	2,375
C_D	0.33	~0.32
Frontal area (m^2)	1.80	~1.85
Engine displacement (cm^3)	91	91
Horsepower	92 @ 6,000	92 @ 5,500
Axle ratio	3.89	3.25
Transmission	M-5	M-5 wide ratio/SIL
Acceleration time, 0-100 kph (secs)	10.6	10.5
City fuel economy (mpg)	36.5	53 (48.5)[a]
Highway fuel economy (mpg)	47.7	67 (62)[a]
Combined fuel economy (mpg)	40.8	59 (54)[a]

[a] California VTEC-E in parentheses. All VTEC-E fuel economy data are approximate.

SOURCE: Energy & Environmental Analysis, Inc., 1991

These features, however, are responsible for less than 10 percent of fuel economy gain, and the EEA sensitivity coefficients reveal that 8 to 9 percent is appropriate for the non-engine/transmission-related benefits.

This suggests a 35-percent gain is possible from the engine/transmission/driveline combination (25 percent for the California car). Honda has reduced the axle ratio by about 16.5 percent between the VTEC-E and the DX. Normally this would reduce performance significantly, but the VTEC engine's variable valve timing enhances low-speed torque. At 2,500 rpm, the torque of the VTEC engine is about 10 percent higher than that for the DX engine. The maximum 92 hp rating is attained at 5,500 rpm in the VTEC engine, while it is attained only at 6,000 rpm in the DX engine. Hence, it appears the VTEC engine provides about 10 percent more power across the entire usable speed range to 5,500 rpm. A wide-ratio transmission with shift indicator light provides further fuel economy benefits, at some expense to shift quality and performance.

The engine also has other enhancements beyond VTEC, such as roller cams, low-friction pistons/rings, and other unspecified friction-reduction technologies. Honda claims that only 10 to 15 percent of the total fuel economy increase is due to the VTEC/lean burn combination. This claim, however, doesn't include the drivetrain optimization made possible by the engine's increased torque output. EEA estimates that at constant performance, the VTEC/lean burn combination may be capable of a 20- to 25-percent increase in fuel economy. This combination cannot meet current California or future Federal emissions standards. Without the lean burn feature, it appears that a 10- to 15-percent benefit may still be possible with VTEC technology, while maintaining all other vehicle attributes constant. This engine can meet both California and future Federal NO_x standards.

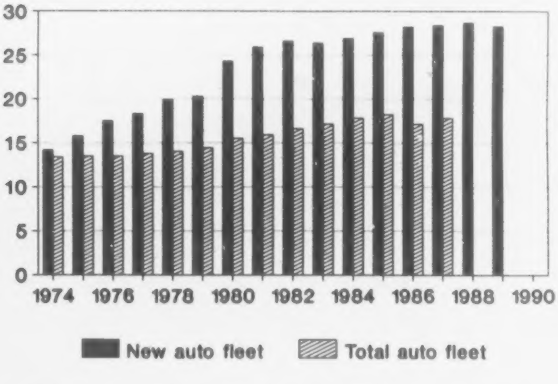
Chapter 4

Market-Driven Fuel Efficiency

There is widespread agreement among energy analysts that, without significant changes in market conditions or government policy, improvements in the efficiency of the U.S. automobile fleet will slow from the pace of the past decade and a half, with most improvements during the next decade coming from diffusion into the fleet of technologies already introduced into the new car fleet. In fact, as shown in figure 4-1, rapid improvements in new-car fuel economy that began in the 1970s essentially ended in 1982—the slowdown has already begun.

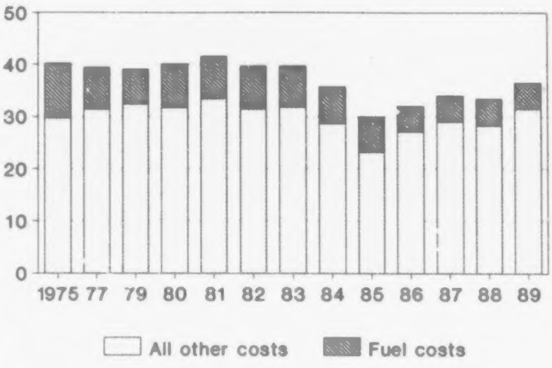
The primary factor reducing potential for rapid increases in fleet fuel efficiency is lack of strong market pressures for such increases. With lower gasoline prices (and lower expectations for price increases), relatively high *non-fuel* vehicle operating costs, and average fuel economy of most new vehicles already in the 20- to 35-mpg range, fuel costs have become a smaller fraction of total costs (figure 4-2) and fuel efficiency has declined dramatically in importance as a factor in choosing a new vehicle. Presuming cost-effective efficiency improvements are available, the overall cost savings over vehicle lifetimes of any efficiency gain will be a small fraction of the total costs of ownership and operation.[1] Also, many technologies that improve fuel economy while maintaining performance and other vehicle attributes will cost more than the technologies they replace and thus will likely raise vehicle price. To the extent that automobile purchasers focus on purchase price rather than on "lifecycle" savings, high-efficiency vehicles may be less marketable than less efficient but lower priced vehicles.[2]

Figure 4-1—Trends in U.S. Auto Fuel Economy
(miles per gallon)



SOURCE: Motor Vehicle Manufacturer's Association, Oak Ridge National Laboratory.

Figure 4-2—Auto Fuel Costs vs. Total Costs
(cents per mile—1986 dollars)



SOURCE: Oak Ridge National Laboratory

Available consumer surveys seem to confirm this. The firm of J.D. Power & Associates conducted an annual survey investigating factors consumers consider important in choosing their next car. In 1980, when most analysts and consumers anticipated rapidly escalating gasoline prices, about a third of the consumers surveyed listed fuel economy as the most important factor they would consider in selecting their next car.[3] This placed fuel economy first among all factors (dependability was second with 24 percent listing it as most important). By 1987, only 3 percent of consumers considered fuel economy their primary selection factor; fuel economy had dropped from first to eighth place in 7 years.[4]

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[1] See, for example, J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, *Energy for a Sustainable World* (Washington, DC: World Resources Institute, September 1987).

[2] Assuming the vehicles are otherwise comparable, which they often are not. NOTE: In today's market, high-efficiency vehicles often are "bottom-of-the-line" models generally *less* expensive than alternative models.

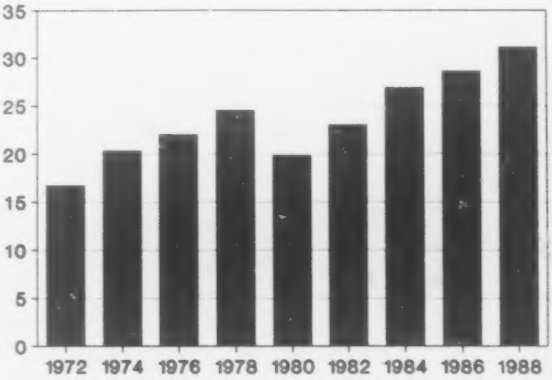
Other factors that may restrain increases in fleet fuel efficiency include:

- **Growth in the use of light trucks for passenger travel.** Although light-truck fuel efficiency has improved markedly since 1974, these vehicles remain substantially less fuel efficient than automobiles. Whereas the average 1990 EPA-rated fleet fuel economy for new automobiles was about 28 mpg, the fleet average for new light trucks was closer to 21 mpg.[5] This disparity in efficiency has a growing influence on overall efficiency of the "light-duty" fleet because sales of light trucks are rising relative to auto sales (figure 4-3) and passenger use of light trucks is growing far more rapidly than use of autos. Light-truck vehicle miles traveled (VMT) grew at a rate more than five times that for autos between 1970 and 1985; during this period, auto vmt increased 38 percent while light truck vmt tripled.[6] And according to 1985 census data, light trucks are used more as passenger vehicles than as freight haulers, making them legitimately part of a light-duty passenger fleet.

  The difference between light-truck and auto efficiency pulled the overall (nominal) new light-duty fleet average down to about 25.4 mpg in 1990,[7] and will likely continue to hold down fleet averages. The growing role of light trucks in passenger travel is a primary cause of recent stagnation in the fleetwide average fuel economy of new light-duty passenger vehicles, which has increased only 1.3 mpg from 1981 to 1990[8]; greater numbers of light trucks in the fleet countered efficiency gains within each portion of the fleet.

- **A growing attraction among purchasers of new automobiles to more powerful (and thus less fuel-efficient) automobiles.** For example, as shown in figure 4-4, average 0-to-60 acceleration time for new vehicles has decreased in every year since 1982. Part of this trend is simply a recapture of performance levels lost earlier to emission con-

Figure 4-3—Sales of Light Trucks As a Percent of All Light-Duty Sales



SOURCE: Oak Ridge National Laboratory

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[3] J.D. Power & Associates, *The Power Newsletter*, Westlake, California, as reported in P.D. Patterson, *Periodic Transportation Energy Report No. 4*, Sept. 8, 1988, and personal communication.

[4] Unfortunately, the survey has not been continued. P.D. Patterson, U.S. Department of Energy, personal communication, Mar. 8, 1991; and John Rettie, J.D. Power & Associates, personal communication, Mar. 8, 1991.

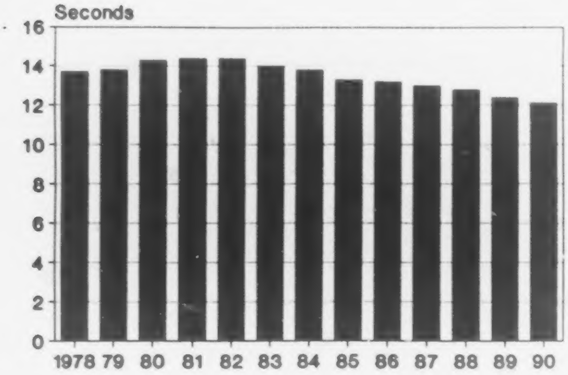
[5] R.M. Heavenrich and J.D. Murrell, U.S. Environmental Protection Agency, "Light-Duty Automotive Technology and Fuel Economy Trends Through 1990," U.S. Environmental Protection Agency, Ann Arbor, Michigan, EPA-AA-CTAB-9003, June 1990, p. 6 (cited hereafter as Heavenrich 1990). The light-truck average is up from about 12 mpg in 1974.

[6] P.D. Patterson, "Analysis of Future Transportation Petroleum Demand and Efficiency Improvements," paper presented at International Energy Agency, Energy Demand Analysis Symposium, Paris, France, Oct. 12-14, 1987.

[7] Heavenrich 1990, op. cit., p. 7.

[8] Heavenrich 1990, op. cit., p. 7.

Figure 4-4—New-Car Performance 0-to-60-mph Acceleration Time



SOURCE: Environmental Protection Agency

trol and satisfaction of CAFE standards; automakers claim new-car owners raised strong objections to reduced power levels in the early 1980s. Although the preference for increased performance may disappear in the future, it is worrisome to those concerned with fuel conservation. An important consequence of this consumer preference has been that drivetrain improvements (such as engines with four valves per cylinder and turbochargers) with the potential to either increase fuel efficiency (at least in part by reducing engine displacement) or boost horsepower have been introduced in configurations emphasizing power increases rather than fuel savings.

The actual reduction in 0-to-60 acceleration time from 1982 to 1990 is 2.3 seconds (from 14.4 to 12.1 seconds), a 16-percent decrease. Based on an EPA analysis of the sensitivity of fuel economy to changes in performance,[9] this decrease has caused more than an 8-percent decline in fuel economy—more than 2 mpg—from what it would have been at 1982-level performance.

- **Additional luxury and safety equipment on new cars.** Although airconditioning and power steering have penetrated more than 80 percent of the fleet, and further increases will be small, other equipment such as power seats, sunroofs, and power locks and windows may gain additional market share and can add significant weight to the vehicle. In addition, four-wheel drive, which can add 150 to 200 pounds to a vehicle and cut its fuel economy by 12 to 15 percent, is gaining popularity. Safety equipment such as airbags (30 to 45 lb) and anti-skid brakes (30 to 45 lb) will add further weight. The net effect of greater penetration of these technologies could be as large as a 3- to 5-percent decrease in fuel economy.[10]
- **More stringent emission standards, especially for nitrogen oxides.** To meet the new Tier I Federal standards on exhaust and evaporative hydrocarbons and nitrogen oxides, manufacturers will choose from alternative strategies that will have tradeoffs in cost, fuel efficiency, and emissions. There are approaches available to manufacturers—e.g., increasing the rhodium content of vehicle catalyst systems—that would meet a more stringent nitrogen oxide standard with a relatively small fuel economy penalty, but at an added cost over alternative approaches.[11] On the other hand, if manufacturers perceive that consumers do not value

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[9] K. Hellman, Chief, Control Technology and Application Branch, U.S. Environmental Protection Agency, Ann Arbor, MI, personal communication.

[10] Energy & Environmental Analysis, Inc., "Developments in the Fuel Economy of Light-Duty Highway Vehicles," contractor report prepared for the Office of Technology Assessment, August 1988.

[11] Sierra Research, Inc., "The Feasibility and Costs of More Stringent Mobile Source Emission Controls," contractor report prepared for the Office of Technology Assessment, Jan. 20, 1988. The report estimates a cost per vehicle of $139 to achieve a 0.25 grams/mile standard for non-methane hydrocarbons and a 0.4 g/mi standard for NO_x with no fuel economy penalty, and no *forgone* fuel economy improvements. The technology involved is an increase in rhodium loadings by 0.5 grams/vehicle in the exhaust catalyst and the addition of a bypassable start catalyst. Another OTA contractor-Energy & Environmental Analysis, Inc.—believes that satisfaction of the above standards would *at least* cause some future fuel economy improvement to be forgone, K.G. Duleep, Director of Engineering, Energy & Environmental Analysis, Inc., personal communication.

fuel economy highly, they may choose control strategies that add little or no cost but sacrifice more fuel economy. In addition, manufacturers could add technologies that have potential for both efficiency improvement and emission control—e.g., multipoint fuel injection—in ways that maximize emission reduction effects but sacrifice some efficiency potential. In these cases, the emission standards would have caused some potential improvement in fuel economy to be forgone. Historically, manufacturers have pursued a variety of strategies to achieve standards: to meet 1981 emission standards, many Japanese manufacturers used oxidation catalyst technology and accepted an efficiency loss of 4 to 6 percent; General Motors met the same standard with "closed loop" electronic fuel control systems with three-way catalysts that incurred no efficiency loss.[12] Energy and Environmental Analysis, Inc. has estimated the potential fuel economy penalty (or gain forgone) of the Tier I standard of 0.4 grams/mile for nitrogen oxides to be about 1 percent, *with significant variation possible depending on how manufacturers balance efficiency against costs.*[13]

- **Slower replacement of the automobile fleet, so that technological improvements introduced into the new car fleet will take longer to diffuse into the total fleet.** In 1969, cars more than 10 years old accounted for only about 7 percent of vehicle miles traveled and fuel consumed; by 1977, such vehicles accounted for about 13 percent of vmt and fuel; and by 1983, they accounted for almost 20 percent of vmt and 23 percent of fuel.[14] In 1989, all light-duty vehicles (not just cars) more than 10 years old accounted for over 30 percent of vmt and roughly 31 percent of light-duty fuel consumption.[15] Note that the importance of turnover rates to total fleet fuel economy and, more significantly, to improved emissions performance indicates that policymakers must avoid strategies that would make new cars less attractive to potential purchasers, and thus slow new-car sales and vehicle turnover.

- **No signs that U.S. drivers will shift to cars with less interior volume.** Although average *exterior* size and vehicle weight have been reduced substantially, with great positive effect on fuel efficiency, and though there have been substantial sales shifts among the different size classes, the average interior volume of new automobiles in the U.S. fleet has remained virtually constant for 13 years: 109 cubic feet in 1978 and 107 in 1990[16] (figure 4-5). On the other hand, the vehicles often cited as demonstrating potential for major fleet efficiency improvements—the very-high-efficiency vehicles in the current fleet and most ultrahigh-efficiency prototypes—are smaller than the average automobile. Although substantial efficiency gains can be made without a shift to smaller (lower interior volume) cars—less than one-tenth (0.5 mpg out of 6.6 mpg total increase) of 1978-1984—progress in new-car efficiency was due to shifts in size class[17]—the apparent difficulty in effecting such a shift limits prospects for future fuel economy gains from fleet downsizing.

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[12] Energy & Environmental Analysis, Inc., 1988, op. cit.

[13] Duleep, op. cit.

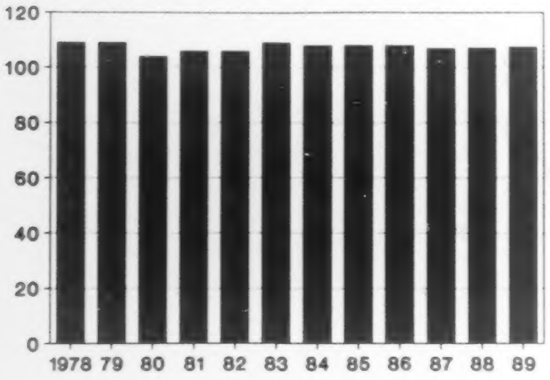
[14] U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Progress Report One: Context and Analytical Framework*, DOE-PE-0080, January 1988.

[15] U.S. Department of Energy, Energy Information Administration, *Household Vehicles Energy Consumption 1988*, DOE/EIA-0464(88), February 1990, p. 29.

[16] Heavenrich 1990, op. cit., p. 17.

[17] P.D. Patterson, "Trends in Automobile Fuel Economy and Energy Use," paper presented at ORSA-TIMS Conference, Boston, MA, Apr. 30, 1985.

Figure 4-5—Interior Volume of New Cars (cubic feet)



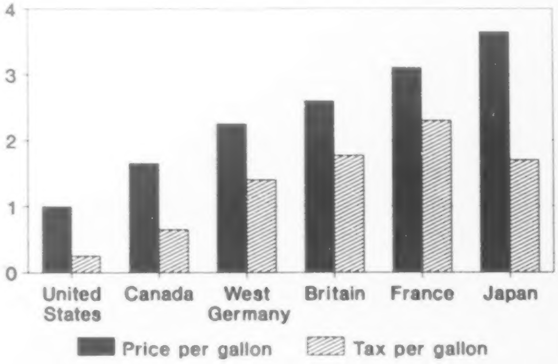
SOURCE: Oak Ridge National Laboratory

- **Continued consumer demand for "old-fashioned" car models.** U.S. manufacturers have found that a portion of new-car purchasers prefer large, heavy, rear-wheel-drive models even though newer, more fuel efficient designs appear functionally superior.[18] Because manufacturers can obtain high profit margins on these models, they have kept them in the fleet despite prior plans to phase them out.
- **Growing road congestion and other factors affecting on-road fuel economy**. Current on-road efficiency of the fleet is estimated to be about 15 percent lower than estimates made with the EPA test procedure. As discussed in box 4-A, changing driving conditions may change the 15-percent adjustment, most likely increasing the gap between EPA and on-road values. In particular, growing congestion may play a major role in reducing fuel economy.

If low oil prices continue, relatively modest benefits to the individual automobile owner of improving fuel efficiency beyond about 30 mpg are unlikely to provide much incentive to manufacturers who must factor in both market risk and the risk of reliability problems into their design and marketing decisions. Manufacturers are likely to be reluctant to introduce major fuel-efficient technology unless it offers other important benefits as well, and they are likely to forgo some potential efficiency benefits to maximize other benefits. Possible side benefits include better emission control characteristics (e.g., from better combustion controls) and improved performance (e.g., from continuously variable transmissions). And despite the existence of some side benefits, improvement in new-car fuel economy is expected to be incremental and quite slow over the next decade or so, assuming the current market environment persists.

Thus, absent sharp increases in world oil prices, oil supply disruptions, or other events that might increase consumer demand for fuel economy, or policy intervention such as gasoline excise taxes (over $2/gallon in many industrial countries, see figure 4-6) and other market incentives (e.g., gas guzzler/sipper fees and rebates), or tightening of CAFE standards, fuel efficiency for the U.S. new vehicle fleet will likely have only modest increases over the next decade as engineering improvements well along in development are gradually introduced. Such technological and design

Figure 4-6—Gasoline Price With Tax (dollars per gallon)



SOURCE: Business Week

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[18] However, rear-wheel drive generally is more suitable than front-wheel drive for trailer towing.

Box 4-A—Potential for Reductions in On-Road Fuel Economy From Changing Driving Patterns

Recent analyses conducted for the Department of Energy[1] conclude that the 15 percent adjustment factor used to translate EPA fuel economy test results to estimated on-road fuel economy is too low for projections of fuel use. First, the share of driving done on urban roads is now substantially higher than the assumed 55 percent; the 1987 share was 63 percent, and the projected share for 2010 is 72 percent.[2] Taking these shifts in the urban/rural share into account would lead to a 1.3-percent decrease in estimated on-road fuel economy for 1987, and a 3.1-percent decrease by 2010. Second, rising urban congestion, caused by a rate of increase in vmt much greater than increases in road capacity in urban areas, will exert a downward pull on on-road efficiency; the estimated effect for 2010 is a 15-percent reduction in EPA city fuel economy, or a 9.1-percent reduction in estimated on-road fuel economy. Third, expected increases in highway speeds will further reduce highway fuel economies; an increase in average speeds from 55.8 mph in 1975 to 59.7 mph in 1987 cost an estimated 0.8-percent reduction from EPA values in on-road fuel economy, with an extrapolation to 66 mph for 2010 yielding an additional 1.6-percent reduction.[3]

The estimated overall effect in 2010 of the three factors depressing on-road fuel economy from EPA-estimated levels—expected increases in the urban share of driving, congestion, and highway speeds—is an additional 14.7-percent reduction from the EPA composite fuel economy on top of the current 15-percent adjustment factor, or a total adjustment factor of 29.7 percent.[4]

OTA judges that quantitative assessments of two of the three forces driving the expected change in adjustment factor are highly uncertain: rising urban congestion and increasing highway speeds. These forces account for nearly four-fifths of the expected adjustment factor increase. In particular, since much highway driving is on *urban* highways, we consider it unlikely that a simple extrapolation of past increases in highway speeds will yield a reliable projection of future highway speeds. We expect the projected 1.6-percent reduction in fuel economy due to increased highway speeds to be an overestimate.

Additional factors that will counterbalance forces adding to the gap between EPA and on-road mileage include:

- the large increase in fuel injection in new cars. The original 15-percent gap was calculated with a fleet made up of carbureted vehicles; the gap is smaller with fuel injected vehicles;[5]
- regulations requiring on-board diagnostics will reduce the number of malfunctioning vehicles, with fleetwide in-use fuel economy benefits;
- regulating evaporative and running losses will reduce fuel lost to evaporative emissions; and
- cold-temperature carbon monoxide emission regulation will reduce fuel enrichment during cold starts at temperatures below 65°F, with in-use fuel savings not recognized by the EPA test, which is conducted at higher temperatures.

We conclude that the DOE estimate of a nearly 30-percent gap between measured and on-road fuel economy in 2010 probably is directionally correct but significantly overstated.

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[1] F. Westbrook and P. Patterson, "Changing Driving Patterns and Their Effect on Fuel Economy," paper presented at the 1989 SAE Government/Industry Meeting, Washington, DC, May 2, 1989.

[2] Ibid.

[3] Ibid.

[4] Ibid.

[5] K.G. Duleep, Director of Engineering, Energy and Environmental Analysis, Inc., personal communication.

improvements and, above all, retirement of older, less efficient vehicles will allow fuel economy of the entire passenger vehicle fleet to rise during the remainder of this century, but at a rate notably below what is achievable.

Longer-term projections of new vehicle fleet fuel economy—to 2010 or beyond—are considerably more speculative because this timeframe allows sufficient lead time for new technologies to play a major role. By 2010, technologies such as two-stroke gasoline and diesel engines, direct injection diesels, even electric/fossil hybrid vehicles could attain significant market shares, with large impacts on fuel economy.

Projections of both new-car and light-duty fleet fuel economy beyond the next few years are at best educated guesses and should be treated as such. Some recent projections include:

- The Energy Information Administration's projection for the year 2000: for new automobiles, 32.6 mpg (EPA); for new light trucks, 24 mpg (EPA); for the entire light-duty fleet, 21 mpg (in use).[19]
- Data Resources, Inc.'s projection for the year 2000: for new automobiles, 30.8 mpg (EPA); for new light trucks, 23 mpg (EPA).[20]

Fuel efficiency could, of course, easily differ from these projections. For example, a combination of factors—additional safety equipment, increases in vehicle performance, more stringent emission standards that are met by least-first-cost (but fuel-inefficient) measures, trends in imports towards larger and more luxurious (and powerful) vehicles, and growing market share for vans and pickup trucks—could make it difficult for the new vehicle fleet to improve significantly beyond today's level. Yet a renewal in consumer and public policy interest in fuel economy could cause fleet efficiency to rise above the projected levels by shifts in market shares of alternative models, more rapid diffusion of existing technology into the fleet, and accelerated introduction of technologies.

Although 1995 fuel economy will be heavily influenced by existing industry plans, fuel economy in 2001 should be much less constrained by such influence, and consequently, especially difficult to predict. *Assuming relatively stable gasoline prices and a general continuation of recent market trends in consumer preferences for vehicle performance, size, and other attributes, OTA's "best guess" for new car fleet fuel economy in 1995 is 29 mpg (EPA value).* We are far less certain of the likely year-2001 value; but under relatively optimistic conditions for increasing fuel economy—oil prices rising by about $10/bbl, fuel economy technologies added to model lines achieving maximum fuel economy benefits consistent with manufacturer tradeoffs with size and performance, and trends to growing vehicle size, power, and luxury leveling out after 1995—we believe the fleet could achieve 33 mpg. Lower oil prices, continued "horsepower wars," less-than-optimal fuel economy performance from new technologies, and so forth, can lower this value significantly.

With the "optimistic" fuel economy scenarios, assuming the 15-percent EPA/in-use fuel economy adjustment will still hold in the future, the in-use values are about 25 mpg for the 1995 new car fleet and about 28 mpg for the 2001 fleet. If urban congestion increases significantly, however, these values will be too optimistic. The corresponding values for the *total* fleet of cars in service are: 27.4 mpg (EPA) and 23.3 mpg (in-use) for 1995; 29.6 mpg (EPA) and 25.1 mpg (in-use) for 2001. With a year-2001 fuel economy value of about 24 mpg (EPA) for new light trucks, the overall light-duty new vehicle fleet average for 2001 would be about 29 mpg (EPA), and the entire light-duty fleet would average about 22 to 23 mpg in-use.[21] If market trends or gasoline prices change significantly, obviously the projections will change, especially for the later years. As will be discussed later, increased consumer preference for the most efficient vehicles in each size class could raise average fleet fuel economy by several miles/gallon even without new technology or radical changes in the size mix of the fleet.

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[19] U.S. Department of Energy, Energy Information Administration, *1991 Annual Energy Outlook*, DOE/EIA-0383(91), March 1991. In-use estimate assumes degradation of efficiency from increasing congestion.

[20] Based on Data Resources, Inc., *Energy Review*, winter 1990-91, table 18, using 0.844 as the ratio of in-use to EPA-rated fuel economy.

[21] Assuming a 15-percent adjustment between fuel economy measured on the EPA test cycle and actual on-road fuel economy.

Chapter 5

Projecting Travel Demand

The likelihood that the market will impede improvements in fleet efficiency is particularly worrisome to energy policy analysts because vehicle miles traveled (vmt), the complementary component of oil use, is widely expected to continue to rise. The rate of increase in light-duty passenger vmt between 1970 and 1988 was very large, about 3.3 percent per year, with auto travel growing somewhat slower (2.5 percent per year), and light-truck travel growing much faster (7.3 percent per year).[1] And the rate of increase in total light-duty travel became larger during 1982-1988: 3.9 percent per year. For the remainder of the century, the rate is likely to be lower, possibly much lower, primarily for demographic reasons; however, sufficient uncertainty exists that the rate of increase conceivably could remain at previous levels.

Figure 5-1 shows that the rise in vmt over the past several decades has been almost constant as expected "saturation points" in auto ownership and travel demand did not occur. Initial assumptions that vehicle saturation would occur at one vehicle per household were surpassed in the United States in the 1930s. Then, a proposed saturation point of one vehicle per worker was surpassed in the mid-1960s. Expected saturation of one vehicle for each licensed driver was surpassed in 1983.[2] For the past 30 years, vmt per vehicle has remained at about 10,000/year, driving total U.S. vmt upward at the rate of expansion of the fleet.[3] The year-by-year rise in travel faltered only twice, and then only for very brief periods when gasoline supply problems were coupled with very sharp price increases.

More than half of the increase in vmt over the previous 15 years can be attributed to the increase in the number of persons of driving age; the remainder was due to the growth in driving per licensed driver and the higher proportion of licensed drivers in the population—the latter due largely to the growth of women in the work force.

The Energy Information Administration's *1989 Annual Energy Outlook*[4] projected personal travel by autos and light trucks to grow at 2.1 percent/year for 1988-2000, reflecting their judgment that the market for such travel would slow somewhat from its steady rate of the past few decades. EIA's most recent forecast, the *1991 Annual Energy Outlook*,[5] has lowered this rate (for 1989-2000) to a projected 1.6 percent/year, with a range of 1.5 to 2.1 percent/year representing scenarios varying from high oil price to low oil price-high economic growth conditions. Other recent forecasts include Argonne National Laboratory: 1.6 percent/year for 1990-2000 (for autos and light trucks)[6]; and DRI: 1.85 percent/year for 1990-2000 (for autos and all trucks)[7,8]. This is an unusually high degree of agreement about a future vmt growth rate that represents a marked shift from previous experience.

OTA agrees that a decreased growth rate for travel is likely. However, there is considerable room for argument about the extent and likelihood of a decrease. On one hand, the previous

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[1] U.S. Department of Transportation, Federal Highway Administration, table VM-201, "Annual Vehicle-Miles of Travel by Vehicle Type and Highway Category, 1936-1985," and annual tables for 1987-89.

[2] P.D. Patterson, "Analysis of Future Transportation Petroleum Demand and Efficiency Improvements," paper presented at IEA Energy Demand Analysis Symposium, Paris, France, Oct. 12-14, 1987.

[3] Ibid.

[4] U.S. Department of Energy, Energy Information Administration, *1989 Annual Energy Outlook*, DOE-EIA-0383(89), Jan. 1989.

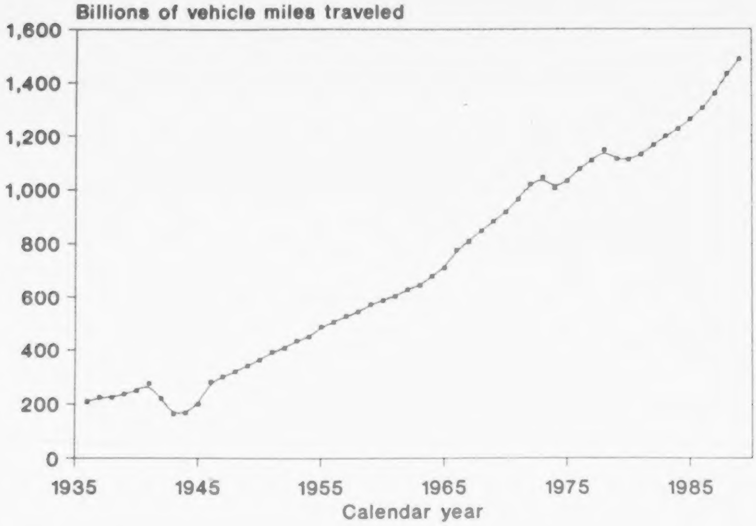
[5] U.S. Department of Energy, Energy Information Administration, *1991 Annual Energy Outlook*, DOE-EIA-0383(91), Mar. 1991.

[6] M. Mintz, Argonne National Laboratory, personal communication, Mar. 25, 1991.

[7] Data Resources, Inc., *Energy Review*, Winter 1990-91, table 18.

[8] *Note:* These forecasts are projecting "personal" travel, excluding vmt for freight hauling by light trucks.

Figure 5-1 —Passenger Car VMT Growth, 1936-89



SOURCE: Office of Highway Information Management.

stability of vehicle mileage trends argues against projecting a significant decrease; on the other hand, demographic factors seem to indicate such a decrease. Factors affecting future vmt include:

- **Women in the work force.** During the past few decades, the growing share of women working (therefore needing to commute) has contributed significantly to rising levels of light-duty vehicle travel. Between 1969 and 1983, the percentage of adult women working rose from 39 percent to 50 percent; and the percentage of those working who had driver's licenses rose from 74 percent to 91 percent. Further increases in the share of women working will continue to affect the demand for transportation services during the next few decades, but *probably* at a considerably slower rate because the current percentage of working women is now high. In fact, by 1988, women made up 45 percent of the total work force, up from 27 percent in 1947.[9]

  The fact that women, working or not, still do not drive nearly as much as men seems to leave open the possibility that changes in lifestyles among women could drive vmt at a higher rate than expected. However, the vmt gap between men and women appears to be caused principally by the social custom of men being the primary drivers for extended, family, and social travel.[10] Were this to change, vmt would be redistributed but not increased.

- **Number of adults.** The rate of growth of adults of driving age will slow as the baby boom passes. After 2010, however, the rate of increase will depend on future birth rates, which are uncertain. A recent surge in birth rates points out the danger in assuming that recent trends will necessarily continue.

- **Possible saturation among high-mileage drivers.** Employed men between 25 and 54 years of age drive more than any other large group-each about 18,000 miles per year, on average. This represents an average of 1.5 hours per day spent driving. Although "common sense" about saturation of driving has been wrong before, it is at least possible that this group may be nearing saturation. One important area of uncertainty: Recent trends in car design making the vehicle interior a more hospitable environment (comfortable seating, excellent climate control, superb music systems, availability of telephone communication, etc.) may increase the likelihood that drivers will tolerate spending more time on the road.

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[9] C.A. Lave, "Future Growth of Auto Travel in the U.S.: A Non-Problem," paper presented at *Energy and Environment in the 21st Century,* Massachusetts Institute of Technology Conference, Mar. 26-28, 1990.

[10] C.A. Lave, op. cit.

- **Changing economic structure.** The growth in part-time work and the shift in the economy toward more services may increase driving by bringing more individuals into the workplace and by increasing delivery requirements. Providing certain types of services, especially information, electronically may eventually replace some transportation, but such trends have not yet been observed.

- **Traffic congestion.** More congestion of metropolitan areas will alter travel patterns. Congestion will decrease fuel efficiency of trips made; discourage other trips (or shift them to public transportation, or to electronic media when possible); persuade some people to work closer to home or live closer to work; and encourage businesses to relocate to the less congested fringes, increasing travel requirements. Net effect on fuel demand is unpredictable.

In OTA's view, the most probable aspects of the above factors are a lower number of persons reaching driving age and a likely slowdown in the rate of women entering the work force, both slowing growth in vmt. Nevertheless, uncertainty associated with various factors affecting travel demand allows a range of feasible growth rates of 1 to 3 percent *without* considering the potential for future oil price shocks. Unexpected large increases in gasoline costs or supply problems could cause growth rates of personal travel demand to fall below these levels, or even cause travel demand to decline. A period of price stability and continued improvements in vehicle designs would make the high end of the range quite plausible.

We note that our projected range of vmt growth extends to a level lower than most projections (e.g., the three projections noted). At the lower end of the range, total fuel use by the fleet will likely decline *unless* negative effects on fuel economy due to growing congestion are very large.

As a final note, we should point out that studies of travel demand indicate that variable travel costs, including fuel cost, affect the magnitude of travel demand. Higher fuel prices will tend to depress travel demand; and increased fuel efficiency, which lowers the "per mile" cost of travel, will tend to boost travel demand. Since travel demand depends on numerous factors that have varied significantly over time, it is not possible to predict precisely how much additional demand for travel might result from actions that boost fuel economy—but analysts agree the effect is significant. In other words, the fuel economy savings expected from an increase in the severity of CAFE standards will be smaller—probably by 10 to 20 percent or so—than if demand for travel were assumed to be unaffected by the new standards.

Chapter 6

Market-Driven Light-Duty Fuel Use

The effect of a combination of moderate improvements in vehicle efficiencies, rising market share of light trucks, and a steady but slightly slower increase in miles driven—which OTA considers the most probable future for personal highway travel during the next decade—will be that, ABSENT POLICY CHANGES, fuel consumption of the passenger vehicle fleet is likely to change only modestly between now and 2001; we project that expected efficiency improvements will nearly offset the expected increase in miles driven.

To be more precise, the fuel efficiency and vmt projections of the Energy Information Administration cited above, indicate that year-2000 fuel use by autos and light trucks combined will be 3.3 percent higher than in 1989. This is a small change for an 11-year period, less than 0.3 percent/year. The range for scenarios varying from "low oil price-high economic growth" to "high oil price" is +10.5 percent to -1.3 percent for the 11-year period.

A projection of relatively stagnant light-duty vehicle fuel consumption conforms to the experience of the previous decade and a half. Between 1973 and 1987, petroleum consumption of the light-duty fleet went from 5.66 mmbd to 6.09 mmbd, an increase of only 7.6 percent.[1] During this period, the in-use fuel economy of the U.S. automobile fleet improved from about 13.3 mpg to 19.2 mpg, and light-truck fuel economy improved from 10.5 mpg to 12.9 mpg[2]—but this increased efficiency was offset by the increase in miles driven. Looked at another way, however, the improvement in efficiency amounted to a savings of about 2.56 mmbd over what oil consumption *would have been* had 1987 driving levels been attained with 1973 fleet efficiency (at $1.00/gallon this would be an annual savings to U.S. drivers of about $40 billion per year).

Alternative projections show only small variations from this. For example, a recent Chevron forecast (*World Energy Outlook*, April 1990) projects an increase of 0.5 percent per year in gasoline demand through 2000.

GOING BEYOND THE MARKET: IMPROVING NEW-CAR FUEL ECONOMY

The next two chapters deal with alternative ways to improve new-car fleet fuel economy—by improving technology and design *within the constraints of existing and projected consumer preferences, assuming no unexpected oil price shocks or large increases in gasoline taxes*; and by changing consumer preferences for fuel economy and other vehicle attributes that influence fuel economy. These alternatives are not independent of each other, because most advances in technology and design yield benefits that can be taken as a variable combination of increased fuel economy and improvements in other vehicle attributes such as performance. The extent to which one or the other is favored is the automaker's decision; the incentive for improving technology and design and the primary influence in making tradeoffs among fuel economy, performance, size, and other attributes is consumer preference.

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[1] Based on table 2.9 in Oak Ridge National Laboratory, *Transportation Energy Data Book, Edition 11*, ORNL-6649, January 1991. *Note:* These values include *all* light trucks, whereas EIA and other projections generally try to exclude light-truck freight use.

[2] Oak Ridge National Laboratory, op. cit., tables 3.11 and 3.19.

Chapter 7

Technological Potential for Increased Fuel Economy

During the past year, Congress has heard a variety of testimony[1] about the technological potential for improving new-car fuel economy. Most of this testimony—including OTA's[2]—focused on defining technological potential in a given year (generally 1995 or 2000) as a single "miles per gallon" value. OTA's motive for selecting a single value was to avoid complicating the fuel economy debate with complex and confusing discussions of scenarios and technical assumptions. We suspect the motives of other analysts discussing this issue were similar.

The problem with this approach is that analysts and others involved in the fuel economy debate have reached no consensus about what "technological potential" really means. Congress has been bombarded with a wide range of estimates of technological potential. Many differences among the various estimates result not from actual differences in technical judgment about the efficiency improvement of specific technologies, though such differences clearly exist, but instead from differences in assumptions about:

- the nature of regulations accomplishing the efficiency change;
- future shifts in the size mix of the fleet;
- changes in acceleration capabilities or other measures of vehicle performance (see box 7-A);
- passage of new safety and emission regulations;
- judgments about an acceptable level of economic disruption to the industry in responding to new fuel economy regulations;
- lead time available to the industry to redesign model lines;
- the time required to develop, perfect, certify, and bring to market new technologies; and
- judgments about consumer response to changes in vehicle costs and capabilities.

Assumptions about these factors must be made in calculating technological potential, since each factor will affect the ultimate fuel economy achieved by the fleet. In addition, there is ongoing argument about whether it is reasonable to expect future *average* levels of technology performance to equal the *best examples* present today, or whether current average performance is a good approximation for performance level five or more years from now. Unfortunately, the focus on developing a single number has tended to obscure assumptions underlying the numbers, with the result that Congress is confronted with estimates that *appear* to be about the same thing, but are not really comparable.

OTA is aware of four general groupings of recent estimates of fuel economy technological potential:

1. Values based on estimates of the efficiency increases associated with individual technologies developed by automobile engineers.[3]
2. Estimates based on statistical evaluations of the current fleet of automobiles. These evaluations try to find correlations between the presence or absence of specific efficiency technologies and differences in vehicle fuel economy. We are aware of two recent

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[1] From the Office of Technology Assessment, Department of Energy, International Association for Energy Conservation, American Council for an Energy-Efficient Economy, Ford Motor Co., Chrysler Corp., General Motors, and the United Auto Workers, among others.

[2] For example, S.E. Plotkin, Office of Technology Assessment, testimony to the Consumer Subcommittee, Committee on Commerce, Science, and Transportation, U.S. Senate, May 2, 1989, "Increasing the Efficiency of Automobiles and Light Trucks—A Component of a Strategy to Combat Global Warming and Growing U.S. Oil Dependence."

[3] These estimates have been made available to the Federal Government but have not been formally published.

Box 7-A—"Constant Performance" and Evaluating Fuel Economy Potential

Most technologies that can improve vehicle fuel economy can also boost performance. Generally, the vehicle designer chooses one to favor because there is a tradeoff between the two. This works as follows: technology might boost engine output without changing engine size (e.g., turbocharging, use of four valves per cylinder, fuel injection, etc.), or instead it might diminish load by reducing friction (e.g., roller bearings, advanced oils) or aerodynamic drag (flush windows, raked windshields). Both outcomes would allow either downsizing the engine to compensate for the power boost or load reduction, thereby improving fuel economy, or leaving the engine the same size and allowing performance to improve (with less or no improvement in fuel economy).

Today, automakers choose to boost performance at the expense of increased fuel economy, primarily because the market rewards performance with profits higher than those attained by adding to fuel economy. In other words, an automaker might be able to charge much more for a boost in acceleration ability than for an equivalent increase in fuel economy. Because many technologies available to improve fuel economy have been used instead to improve performance, measuring the *potential* fuel economy performance of these technologies demands that their measured fuel economy effects be adjusted to a baseline of constant performance. There are two important analytical problems associated with this adjustment.

First, the technology will have been developed for maximum performance rather than maximum fuel economy, so a simple adjustment to constant performance may hide some of the technology's potential. Second, there may be disagreement about what "constant performance" actually means. As an example, 4-valve-per-cylinder engines allow a significant horsepower increase over baseline 2-valve engines without increasing engine displacement — 50-percent horsepower increases are not unusual. However, maximum horsepower is achieved in a 4-valve engine at significantly higher rpm than in 2-valves; also, the low end torque (torque achieved at low rpm) is only modestly higher for the 4-valve than for the 2-valve. This means that a downsized 4-valve engine with identical horsepower to a larger 2-valve will have a considerably different, probably inferior, driving "feel", and will have less low end response. Consequently, horsepower and the horsepower/weight ratio are unsatisfactory measures of performance *by themselves*. To complicate matters, different automakers, all of whom aim to distinguish the driving feel of their vehicles from those of other makers, will reach different conclusions about how much engine downsizing, and thus how much added fuel economy, can be gained from a particular technology. Those willing to create a high-revving vehicle with an active automatic transmission might be willing to downsize engines considerably more than a maker intent on creating a vehicle with a smooth, low-revving feel.

This complexity creates a policy problem as well as an analytical one. Is it valid to argue that a new fuel economy standard is flawed because it would require changing the feel of a company's vehicles—especially when vehicles with the type of feel that may be required are successfully marketed (though not necessarily to all types of customers)? This problem goes to the heart of the inherent tradeoff between regulatory goals and values such as consumer choice. Virtually any regulation that is at all stringent will tend to limit consumer choice. The issue is to define an acceptable limit.

statistical evaluations, both sponsored by the industry.[4]

3. Estimates based on extrapolation from experience with ultra-high-mileage vehicles in the fleet, vehicle prototypes, and laboratory results of specific fuel economy technologies, perhaps coupled with assumptions about possible shifts in consumer preferences. Early estimates by the energy conser-

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[4] J.O. Berger, M.H. Smith, and R.W. Andrews, "A System for Estimating Fuel Economy Potential Due to Technology Improvements," Sept. 24, 1990, Preliminary Report; and W.V. Bussmann, Chrysler Corp., "Potential Gains in Fuel Economy: A Statistical Analysis of Technologies Embodied in Model Year 1988 and 1989 Cars," Feb. 15, 1990.

vation community relied heavily on estimates of this type.[5]

4. Values based on estimates of efficiency increases associated with individual technologies and potential for increased penetration of these technologies developed by Energy and Environmental Analysis, Inc. (EEA), under the sponsorship of OTA, the Department of Energy, and the Environmental Protection Agency. DOE, OTA, and the American Council for an Energy-Efficient Economy (Ledbetter and Ross) have all presented estimates of technological potential based on the EEA estimates.[6]

In addition, two recently initiated efforts are considering the same issue. The Motor Vehicle Manufacturers Association (MVMA) has contracted with SRI International to conduct a study of the fuel economy potential of existing technology and has arranged access to confidential industry data and analysis to complete the work. The Department of Transportation has asked the National Research Council to undertake a similar study. Both studies are short-term in nature, due within the year.

Efforts thus far have produced results that fall roughly into three categories. First, estimates provided by the energy conservation community indicate a very high level of fuel economy potential for the fleet. The American Council for an Energy-Efficient Economy calls for a CAFE standard of 45 mpg for cars and 35 mpg for light trucks by the year 2000. Other estimates of technological potential range to 60 mpg and higher for the early 21st century.

Second, estimates produced by EEA for the automobile fleet are in the 30- to 38-mpg range depending on timeframe (1995 or 2001) and scenario (from no change in fleet size mix and power and conservative investment assumptions, to significant rollbacks in size and power and investment assumptions based on societal rather than private interests). Recent EEA estimates for 2010 project a considerably higher potential, to 45 mpg or higher.

Third, industry estimates and industry-sponsored statistical evaluations indicate minimal fuel economy potential for the near term (to 1995 or 2000/2001), with much of that potential required to offset fuel economy penalties associated with new emission controls and safety standards.

Both EEA estimates and available industry and industry-sponsored estimates for 1995 and 2000/2001 are basically conservative, at least from a technology standpoint, because they consider only technologies already introduced into the fleet. As discussed below, in considering a timeframe that extends to the year 2000 and a bit beyond, there is a distinct possibility—even a probability—that technologies not yet in the fleet will play a role in improving fuel economy.

ENGINEERING ANALYSES OF FUEL ECONOMY TECHNOLOGIES PERFORMED BY DOMESTIC AUTOMAKERS

The three domestic automakers—Chrysler, Ford, and General Motors—have attempted to duplicate the EEA fuel economy analyses using values derived by their vehicle engineers for the fuel economy potential of each technology. Results of these analyses were first presented and discussed at a meeting in Detroit on January 17, 1990, attended by representatives of the automakers, DOE, DOT, EPA, and OTA and K.G. Duleep of EEA (the principal investigator for EEA's work).

Tables 7-1, 7-2, and 7-3 present, respectively, the Department of Energy's 1989 estimates of fuel economy for 1995 and three scenarios for 2000

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[5] For example, D.H. Bleviss, *The New Oil Crisis and Fuel Economy Technologies* (Westport, CT: Greenwood Press, 1988).

[6] For example: C. Difiglio, K.G. Duleep, and D.L. Greene, "Cost Effectiveness of Future Fuel Economy Improvements," *The Energy Journal*, vol. 2, No. 1, 1990, pp. 65-83; M. Ledbetter and M. Ross, "Supply Curves of Conserved Energy for Automobiles," *Proceedings of the 25th Intersociety Energy Conservation Engineering Conference*, American Institute of Chemical Engineers, New York, NY, 1990; and S.E. Plotkin, Office of Technology Assessment, op. cit.

Table 7-1—Passenger-Car Fuel Economy Projections: Assessment of Technology Potential at Hypothetical Usage Rates*

(all figures given as percentages)

	Department of Energy			1995 v. 1987 DOE Product Plan		2000 v. 1995 DOE Product Plan		2000 v. 1995 DOE Cost-Effective		2000 v. 1995 DOE Max. Technology	
Technology	1985 v. 1987 F.E.	2000 v. 1995 Gain	1987 Industry Usage	Usage	mpg Gain	Usage	mpg Gain	Usage	mpg Gain	Usage	mpg Gain
Engine Improvements											
Intake Valve Control	10.0	10.0				20	2.00	50	5.00	70	7.00
Overhead Cam Engine	6.0	6.0	24	69	2.70	99	1.80	99	1.80	99	1.80
Roller Cam Followers	1.5		55	95	0.60	95		95		95	
Low-friction Pistons and Ring	2.0		20	100	1.60	100		100		100	
Adv. Friction Reduction		2.0				80	1.60	80	1.60	80	1.60
Throttle-body Fuel Injection	3.0		28	40	0.36						
Multipoint Fuel Injection	3.0	3.0	48	60	0.36	100	1.20	100	1.20	100	1.20
4-Valve 6-Cyl. for 8-Cyl.	10.0	10.0		12	1.20	16	0.40	20	0.80	20	0.80
4-Valve 4-Cyl. for 6-Cyl.	10.0	10.0		18	1.80	24	0.60	30	1.20	30	1.20
4-Valve 4-Cyl. for 4-Cyl.		5.0				10	0.50	40	2.00	50	2.50
Transmission Improvements											
Electronic Control	1.5			80	1.20						
Torque Converter Lock-up	3.0		60	80	0.60						
4-spd Automatic (v. 3-spd L/Up)	4.5		40	80	1.80						
5-spd Automatic		2.5				10	0.25	20	0.50	40	1.00
CVT		2.5				10	0.25	40	1.00	40	1.00
Other Improvements											
Front-wheel Drive	10.0	10.0	74	86	1.20	95	0.90	99	1.30	99	1.30
Weight Reduction (Materials)		6.6								80	5.28
Aero. Drag Reduction I	2.3		20	100	1.84						
Aero. Drag Reduction II		2.3				10	0.23	10	0.23	80	1.84
Electric Power Steering		1.0				5	0.05	5	0.05	60	0.60
Lubricants/Tires	1.0			100	1.00						
Tires		0.5				20	0.10	100	0.50	100	0.50
Accessories	1.0	1.0	20	100	0.80						
Total Fuel Economy Increase					17.1		9.9		17.2		27.6

* Usage rates are for comparison only. Their use does not imply manufacturing or marketing feasibility.

SOURCE: General Motors, Ford, Chrysler

Table 7-2—Passenger-Car Fuel Economy Projections: Assessment of Technology Potential at Hypothetical Usage Rates*
(all figures given as percentages)

	DOE		Chrysler							
	Fuel Economy Gain				1995 v. 1989		2000 v. 1995		2000 v. 1995 Max. Technology	
Technology	1995 v. 1987	2000 v. 1995	Engineering Assessment Fuel Economy Gain	1989 Usage	DOE Usage	Chrysler mpg Gain	DOE Usage	Chrysler mpg Gain	DOE Usage	Chrysler mpg Gain
Engine Improvements										
Intake Valve Control	10.0	10.0	2.0				20	0.40	70	1.40
Overhead Cam Engine	6.0	6.0	nil	98	69	–	99		99	
Roller Cam Followers	1.5		2.4	76	95	0.46	95		95	
Low Friction Pistons and Ring	2.0		0.5	50	100	0.25	100		100	
Adv. Friction Reduction		2.0	nil				80		80	
Throttle-body Fuel Injection	3.0		3.4 a	63	40	(0.78)		(1.36)		(1.36)
Multi-Point Fuel Injection	3.0	3.0	4.9 a	35	60	1.23	100	1.96	100	1.96
4-Valve 6 Cyl. for 8 Cyl.	10.0	10.0	5.0 b		12	0.60	16	0.20	20	0.40
4-Valve 4 Cyl. for 6 Cyl.	10.0	10.0	5.0 b		18	0.90	24	0.30	30	0.60
4-Valve 4 Cyl. for 4 Cyl.		5.0	5.0 b				10	0.50	50	2.50
Transmission Improvements										
Electronic Control	1.5		0.5	24	80	0.28				
Torque Converter Lock-up	3.0		3.0 c	79	80	0.03				
4-spd Automatic (v. 3-spd Lock-up)	4.5		2.0	24	80	1.12				
5-spd Automatic		2.5	2.0 d				10	0.20	40	0.80
CVT		2.5	2.0 d				10	0.20	40	0.80
Other Improvements										
Front-Wheel Drive	10.0	10.0	1.0 e	98	86	–	95	–	99	0.01
Weight Reduction (Materials)		6.6	5.0 f	base					80	4.00
Aero. Drag Reduction I	2.3		2.5 g	base	100	2.50				
Aero. Drag Reduction II		2.3	3.0 g	base			10	0.30	80	2.40
Electric Power Steering		1.0	1.0 h				5		60	0.60
Lubricants/Tires	1.0		0.5	base	100	0.50				
Tires		0.5	0.5	base			20	0.10	100	0.50
Accessories	1.0	1.0	nil i	100						
Total Fuel Economy Increase						7.1		2.8		14.6

*Usage rates are for comparison only. Their use does not imply manufacturing or marketing feasibility.

NOTES:
- a vs carburetor
- b Fuel economy effect of 10% displacement reduction with same power level
- c All 4- and 5-spd include Lock-up
- d vs 4-spd Lock-up
- e Net of drivetrain losses (-1%) and one TWC reduction (+2%)
- f Assumes 10% weight reduction
- g Aero I: C_D reduction of .05 from 1989, Aero II: .05 C_D reduction from 1995
- h Not counted pending resolution of feasibility issues
- i Gains offset by potential loss to CFC regulations

SOURCE: General Motors, Ford, Chrysler.

Table 7-3—Domestic Industry Analyses of OTA Technology Assessment: Fuel Economy Benefit of Each Technology at OTA Penetration Increase Where Possible (all figures given as percentages)

	OTA				Domestic Industry Estimate Sales Weighted Average		
Technology*	OTA's Est Fuel Economy Gain	OTA's Est Fleet Penetration 1987	Fleet Penetration 1995	OTA's Est Fleet Fuel Economy Gain	Industry Fuel Economy Gain	Fleet Penetration 1989	Fleet Potential Fuel Economy Gain
Front-wheel Drive	12.0	78.0	88.0	1.2		81.8	0.1
• Drivetrain Efficiency					nil		
• Package, Weight (1 TWC)					2.0		
4-Cylinder/4-Valve	7.5	5.0	45.0	3.0	3.7	4.3	1.5
4-speed Auto/CVT	7.5	35.0	75.0	3.0	3.4	47.4	0.9
• 3-Speed Non-L/Up to L/Up							
• 3-Speed L/Up to 4-Speed L/Up							
Electronic Trans Control	1.5	2.0	82.0	1.2	0.2	3.4	0.2
Aerodynamics from 0.37 to 0.32	3.4	N/A	100.0	3.4	3.0	1.7	2.9
Tires	0.5	N/A	100.0	0.5	0.5	4.8	0.5
Accessories	1.0	N/A	100.0	1.0	1.0	90.6	0.1
Engine Improvements							
• Overhead Camshaft	6.0	40.0	60.0	1.2	1.1	24.8	0.4
• Roller Cams	1.5	40.0	80.0	0.6	2.2	47.0	0.7
• Low-friction Rings/Pistons	1.5	N/A	80.0	1.2	1.5	61.1	0.3
• Throttle-body Fuel Injection (over carburetor)	3.0	31.0	41.0	0.3	2.4	34.0	0.0
• Multipoint Fuel Injection (over carburetor)	7.0	45.0	55.0	0.7	1.3	64.8	0.0
Total 1995 Fuel Economy Improvement				17.3			7.6

* OTA Assumption of Attainable, Cost-Effective Fuel Technologies: 1995 gasoline price - $1.10/gallon (1987$); 4-year timeframe for fuel savings; 10% discount rate (OTA considers these technologies to be "off-the-shelf").

These improvement percentages are overly optimistic because they do not consider the applicability to a full-line manufacturer's product line and penetration rates or the effect of more stringent emissions and proposed safety standards.

SOURCE: General Motors, Ford, Chrysler

(these estimates have since been revised); Chrysler Corp.'s alternative estimates for 1995 and two of the three year-2000 scenarios, assuming the same technology penetrations used by EEA, for comparison; and a direct comparison between an earlier OTA fuel economy estimate for 1995 and the three automakers' combined estimate. DOE's and OTA's estimates were produced by EEA.

STATISTICAL ANALYSES OF FUEL ECONOMY PERFORMANCE OF TECHNOLOGIES IN THE EXISTING FLEET

The domestic industry has sponsored two statistical analyses of the existing auto fleet to derive regression equations relating the fuel economy of autos to both measured variables (vehicle weight, engine displacement, and so forth) and the presence or absence of specific technologies. The equations can be used to estimate the fuel economy impact of the technologies, and this in turn can be used to project the fuel economy impact of a fleet employing these technologies to a different degree. The Bussmann (Chrysler) analysis[7] uses data from the 1988 and 1989 fleets; the Ford-sponsored Berger, Smith, and Andrews, or BSA, analysis[8] uses 1988-90 data.

The BSA analysis derives regression equations for fuel economy in a form having the dependent variables as the natural logs of city and highway fuel economy and the independent variables as the natural logs of such vehicle-related variables as test weight, the ratio of engine rpm to vehicle velocity in top gear, engine displacement and compression ratio, and so forth. The natural log form was chosen because, according to the authors, many improvements associated with various technologies should be multiplicative rather than additive. A number of the independent variables are "indicators," set to 1.0 if a certain technology (multipoint fuel injection, overhead cam engine) is present and zero if it is not. Since adding technologies to the fleet has often been accompanied by changes in performance, the equations are adjusted to find the effect of each technology at constant performance. This is accomplished by asking Ford engineers, "If this technology improvement is added to a vehicle, in order to keep performance constant, what other characteristics of that vehicle will have to change, and by how much?" Asking this question rather than the more direct, "If this technology is added, what will be the impact on fuel economy?" minimizes bias on the part of industry engineers who might answer conservatively if the question were in the latter form.

The BSA analysis estimated that the U.S. fleet would obtain an increase in fuel economy from 1987 to 1995 of 7.19 percent from the technologies in table 7-1, not counting the effects of low-friction pistons and rings, lubricants, and accessories, which were not modeled. The comparable DOE value[9] is 13.66 percent, whereas the corresponding industry values range from 7.23 to 7.64 percent. For the 1995-2000 period, BSA estimates a 12.91 percent gain for the technologies in table 7-1 not counting intake valve control, advanced friction reduction, five-speed automatic transmission, continuously variable transmission, and electric power steering. Comparable figures are 16.42 percent for DOE's analysis and between 9 and 11 percent for the analyses of the three domestic automakers.

The Bussmann analysis consists of a multiple regression analysis of data from 1,400 cars in the 1988- and 1989-model-year EPA databases, supplemented with industry-supplied information on camshaft arrangement, number of valves per cylinder, type of fuel injection, use of low-friction internals, and turbocharging.[10] Unlike the BSA analysis, Bussmann uses no engineering judgments—his is a purely statistical approach, with the only judgment being the selection of independent variables. Of particular interest in this selection is Bussmann's dividing engines into four basic categories that incorporate groups of engine technologies. He found that, given a paucity of data on separate engine technologies, this arrangement yielded a more reliable statistical model than one using individual engine technologies as the independent variables.

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[7] See footnote 4.

[8] See footnote 4.

[9] According to the BSA analysts.

[10] V. Bussmann, op. cit.

The group of technologies that OTA calculated would yield a 17.3-percent fuel economy increase from 1987 to 1995 would instead, according to Bussmann's model, give a 5.4-percent increase from 1989 to 1995. Although the baseline years are different, there is no doubt the OTA (EEA) model and Bussmann's are radically different. For example, Bussmann's estimate of the unit gain for aerodynamic improvements is 1.8 percent versus EEA's 3.4 percent; and Bussmann's estimate for all engine improvements is 6.2 percent versus EEA's 17 to 20 percent.

ARGUMENTS OF THE ENERGY CONSERVATION COMMUNITY

Analysts from the energy conservation community have marshalled a variety of arguments supporting the proposition that efficiency of the U.S. light-duty new car fleet can be greatly increased over the next 20 years.[11] In general, they assert that U.S. auto fleet fuel economy can be raised to 45 mpg or higher by 2000, and considerably more within the following one or two decades. Unlike the industry and EEA analyses, which focus primarily on technological change,[12] the conservation community clearly envisions change in *both* technology and customer preferences.

First, the conservation community argues that government action could change market pressures that have held down gains in fleet efficiency during the 1980s. In particular, lower gasoline prices have reversed trends toward smaller cars and dropped the market shares of fuel efficiency leaders such as the VW Rabbit diesel. Presumably, government actions to raise gasoline prices, raise the purchase price of fuel-inefficient vehicles, and possibly lower the purchase price of fuel-efficient vehicles could substantially increase fleet efficiency even without new technologies, by encouraging purchasers to choose cars in lower size classes or more fuel-efficient models in each size class, and encourage manufacturers to use available fuel efficiency technologies more widely in their fleets. In the longer run, these actions would encourage manufacturers to develop new technologies and consumers to purchase them.

Second, the conservation community claims a variety of fuel efficiency technologies exist, in fully commercialized form, that are not disseminated through the fleet as widely as they could be. Table 7-4 lists technologies whose introduction or wider use offers a potential to improve fleet fuel efficiency.

Third, several car manufacturers have produced vehicle prototypes reported to achieve very-high fuel efficiency (see table 7-5). The conservation analysts contend the existence of these prototypes provides concrete evidence of the

Table 7-4—Developed and Near-Term Fuel Economy Technologies

- Engine Improvements
  - 4 valves per cylinder
  - Overhead camshaft
  - Roller cam followers
  - Low-friction rings/pistons
  - Throttle-body fuel injection
  - Multipoint fuel injection
  - Intake valve control

- Four-speed automatic transmission
- Electronic transmission control
- Aerodynamics, $C_D = 0.30$
- Tire improvements
- Lubricants (5W-30)
- High-efficiency accessories

SOURCE: Energy & Environmental Analysis, Inc.

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[11] See F. Von Hippel and B. Levi, "Automobile Fuel Efficiency: The Opportunity and the Weakness of Existing Market Mechanisms," *Resources and Conservation*, pp. 103-124, 1983, and D.L. Bleviss, *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s* (Westport, CT: Quorum Books, 1988).

[12] Though these analyses do allow the potential for a rollback in performance and size to 1987 levels.

Table 7-5—High-Efficiency Automobile Prototypes

Prototype	Fuel	Fuel Economy (mpg)	Passenger Capacity
VW Auto 2000	diesel	66	4-5
Volvo LCP 2000	multifuel	69	2-4
Renault EVE + ...	diesel	70	4-5
Toyota Ltwt Compact ..	diesel	98	4-5

NOTE: Fuel economies converted to equivalent EPA test values, using conversion factors recommended by the International Energy Agency. Details and further descriptions of the vehicles are in the source document. Vehicles do not necessarily meet all U.S. emissions or safety requirements.

SOURCE: Table 10. "Fuel Economy for Passenger Automobiles," in J. Goldemberg et al., *Energy for a Sustainable World*, World Resources Institute, Washington, DC, September 1987.

Table 7-6—Future Technologies for Improving Light-Duty Vehicle Efficiency

Variable-geometry turbochargers	Increases effectiveness of turbocharging at low loads, allows engine downsizing.
Improved electronic controls	Adjustment of engine operating parameters (e.g., ignition timing) based on direct measurement of cylinder pressure and other operating conditions.
Advanced lubricants (solid and gaseous).	
Oxygen enrichment of air intake	Using membrane technology to enrich oxygen content of intake air. Effect similar to, but more effective than, turbocharging.
Adiabatic diesel.	Low-heat-rejection engine achieved by heavy use of ceramics. Couples removal of cooling requirement and capture of exhaust energy through turbocharging or supercharging.
Continuously variable transmissions	Allows engine to be kept at optimum operating speed throughout the driving cycle. Currently available for small engines only.
Advanced materials	Substantial weight reduction through use of improved plastics and future use of high-strength steels, aluminum, magnesium, ceramics.
Advanced tires.	Reductions in rolling resistance through improvements in design or use of advanced materials (e.g., liquid-injection-molded polyurethane).
Engine stop-start and energy storage.	Engine shutdown during idle and braking, coupled with flywheel storage to power accessories and aid to restart.

SOURCE: D.L. Bleviss, *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s* (Westport, CT: Quorum Books, 1988).

high, long-term potential for improving fleet efficiency.

Finally, technologies at various stages of development have been identified that show promise of large efficiency gains. For example, new designs of a two-stroke engine for automobile applications are said to be capable of fuel economy gains of 20 percent or more over conventional four-stroke engines with concurrent reductions in manufacturing costs.[13] Another engine said to hold considerable promise is the direct-injection diesel. Table 7-6 lists potential efficiency technologies identified by one conservation analyst. Advocates of higher fuel economy standards and other efficiency-oriented policy actions believe such measures will speed development and introduction of these technologies.

Analysts associated with the American Council for an Energy-Efficient Economy have proposed a year-2000 efficiency goal for new vehicles of 45 mpg (EPA) for autos and 35 mpg for light trucks.[14] Achieving these goals would raise average in-use fleet fuel economy to about 27 mpg by 2000, up from a projected level of about 22 mpg. If total annual mileage traveled were 2.21 trillion miles, this efficiency improvement (27 v. 22 mpg) would save about 1.2 mmbd of oil or, at $1.00/gallon, over $20 billion per year by 2000, and more in future years as the technology diffused into the fleet. The energy conservation community argues that these goals are both technically attainable and cost-effective even at today's gasoline prices, based on available vehicle prototypes and cost and performance analyses for a variety of individual technologies.

THE EEA ESTIMATES

EEA has developed estimates for 1995 and 2001 fuel economy (under alternative conditions) for that portion of the U.S. automobile fleet manufactured by General Motors, Ford, and Chrysler, and the portion manufactured by the five largest Japanese manufacturers. Estimates for the entire fleet can be developed by estimating relative market shares and adjusting for vehicles manufactured by automakers not included (e.g., Volkswagen, Hyundai).

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[13] "Detroit Gets Serious About Two-Stroke Engines," *Business Week*, July 18, 1988. Also, see D. Plohberger, L.A. Mikulic, and K. Landfahrer, AVL-List GmbH, Graz, Austria, "Development of a Fuel Injected Two-Stroke Gasoline Engine," SAE Technical Paper Series #880170, 1988.

[14] W.U. Chandler, H.S. Geller, and M.R. Ledbetter, *Energy Efficiency: A New Agenda*, American Council for an Energy-Efficient Economy, Washington, DC, July 1988. The authors suggest several policies to complement and help achieve this goal, including gasoline taxes, new "gas-guzzler" taxes, and a "gas-sipper" rebate program. They also suggest that efficiency standards be carefully structured to avoid past problems of unfairness, for example, by basing them on vehicle interior volume.

EEA's methodology, described in more detail in appendix A, first specifies a baseline of fuel economy and vehicle technology attributes for each market class.[15] For each vehicle type, EEA has identified individual fuel economy technologies applicable to that type and the fuel economy benefits associated with each technology.[16] The methodology then adopts these technologies and calculates total fuel economy benefits subject to constraints about synergism between technologies and non-additivity of certain types of benefits. Selection of the technologies is also subject to a variety of assumptions adopted by the client, including lead-time constraints and rules defining cost-effectiveness (discount rates, total years of fuel savings in the analysis). For the near term (1995), announced company product plans are used to define minimum technology improvements associated with major subsystems. As a last step, the estimates of total fuel economy benefits are adjusted for expected changes in weight and performance of the fleet, and changes in emissions and safety standards.

The list of technologies and fuel economy benefits used in the analysis was compiled using data from research papers, actual benefits from vehicles already featuring the technology, manufacturer submissions to the Department of Transportation, and in some cases, information obtained directly from manufacturers. The EEA estimates of individual technology benefits have been extensively discussed with domestic manufacturers and some foreign manufacturers as well, and EEA has revised some of their individual estimates on the basis of manufacturers' comments.

Tables 7-7 through 7-11 provide EEA's projections for 1995 domestic and Japanese new car fleet fuel economy assuming a "product plan" scenario wherein industry installs technology at rates that correspond to published plans for most major components and make economic sense from a purely market-driven perspective for minor components.[17] The projection further assumes a continuation of current trends in increasing vehicle size and performance and application of expected emissions and safety standards. In other words, in 1995:

- With no new fuel economy regulations nor other policies that could alter fuel economy (e.g., gasoline taxes), and no significant changes in market forces, domestically manufactured new car fleet fuel economy will be about 28.3 mpg. The import car fleet will be at about 31.1 mpg. Total new car fleet fuel economy will be about 29.2 mpg assuming a 35-percent import share.
- If the size and performance of the new car fleet could somehow be rolled back to 1987 levels, and if emission and safety standards could be met without fuel economy penalties, the domestic and total new car fleet fuel economies would be about 31 mpg and 32.5 mpg. *This is a theoretical case to show the effects of market and regulatory changes, not a realistic scenario.*

The above discussion focuses on attainable levels of fleet fuel economy in the absence of significant changes in consumer preferences for fuel economy, power, and other features that affect fuel economy. If buyer preferences *do* change, in response to higher oil prices, actual or expected gasoline shortages, or strong leadership on the part of the President or Congress, 1995 new car fleet fuel economies could be higher than the values cited. The mechanism for higher values would likely be an increased preference *within*

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[15] The market classes are minicompact, subcompact, compact, sports, intermediate, large, and luxury.

[16] The fuel economy benefits are calculated at constant performance and interior volume. This is necessary because fuel economy technologies can typically be used to increase performance or interior volume with less or no improvement in fuel economy, if the vehicle designer so desires.

[17] Components are assumed to be adopted if they save enough fuel to compensate for any increase in vehicle sales price caused by adoption, using a discounted cash flow calculation.

Table 7-7—Projection of U.S. Domestic Manufacturers Fuel Economy 1995 Product Plan Case (does not include test adjustments)

Technology	Penetration Fuel Economy Gain (%)	Increase from 1987(%)	1995 Penetration (%)	Fleet Fuel Economy Gain (%)
Front Wheel Drive	10.0	12	86	1.20
Drag Reduction (C_D = 0.33)	2.3/4.6**	65/15	100	2.19
Four-speed Automatic Transmission	4.5	40	80	1.80
Torque Converter Lock-up	3.0	20	80	0.60
Electronic Transmission Control	0.5	80	80	0.40
Accessory Improvements	0.5	80	N/M***	0.40
Lubricant/Tire Improvements	1.0	100	100	1.00
Engine Improvements				
Advanced Pushrod	3.0	(40)****	(30)	1.20
Overhead Camshaft	3.0	45	69	1.35
Roller Cam Followers	2.0	40	95	0.80
Low-friction Pistons/Rings	2.0	80	100	1.60
Throttle-body Fuel Injection	3.0	12	40	0.36
Multipoint Fuel Injection (over throttle body)	3.0	12	60	0.36
4-valves-per-cylinder-Engine				
4-Cylinder replacing 6-cylinder*	8.0	18	18	1.44
6-Cylinder replacing 8-cylinder*	8.0	12	12	0.96
Total Fuel Economy Benefit (%)				15.66

*1987 distribution: 20.5% V-8, 29.5% V-6, 50% 4 cylinder

**Drag reduction for large/luxury cars from C_D = 0.42 baseline

***N/M - not meaningful

****( ) this includes upgrades from old pushrods to both advanced pushrods and overhead cam engines (for which an incremental benefit is taken)

SOURCE: Energy & Environmental Analysis, Inc.

Table 7-8—Import Manufacturers Fuel Economy Five Largest Japanese Manufacturers Only (does not include test adjustments)

Technology	Fuel Economy Gain (%)	Penetration Increase from 1988(%)	1995 Penetration (%)	1995 Fleet Fuel Economy Gain (%)
Front-wheel Drive	5.0	3	90	0.15
Drag Reduction I	2.3	80	100	1.84
Four-Speed Automatic Transmission	4.5	16	47	0.72
Torque Converter Lock-up	3.0	9	53	0.27
Electronic Transmission Control	0.5	44	47	0.22
Accessory Improvements	0.5	80	N/M***	0.40
Lubricant/Tire	1.0	100	100	1.00
Roller Cam Followers	2.0	50	50	1.00
Low-friction Pistons/Rings	2.0	80	100	1.60
Throttle-body Fuel Injection**	2.0	25	20	0.50
Multipoint Fuel Injection	3.0	20	75	0.60
4-valves-per-cylinder Engine	5.0	20	44*	1.00
Total Fuel Economy Benefit (%)				9.30

*Additional 6 percent are 3 valves/cylinder.

**Benefit of TBFI is lower than for domestic cars because air pumps are not used in carburetted import cars.

***N/M - not meaningful

SOURCE: Energy & Environmental Analysis, Inc.

Table 7-9—1995 Product Plan U.S. Domestic Auto Fleet (does not include test adjustments)

	(mpg)
1987 fuel economy	26.7
1995 fuel economy (without size or performance increase)	30.9
Size/weight increase	-1.4
Performance increase	-0.7
Effect of emission/safety standards	-0.8
1995 product plan fuel economy	28.0

SOURCE: Energy & Environmental Analysis, Inc.

Table 7-10—1995 Product Plan Import Manufacturers (does not include test adjustments)

	(mpg)
1988 fuel economy	31.4
1995 fuel economy (without size or performance increase)	34.32
Size/weight increase	-1.66
Performance increase	-0.90
Effect of emission/safety standards	-0.94
1995 product plan fuel economy	30.82

SOURCE: Energy & Environmental Analysis, Inc.

size classes for the more fuel-efficient models and a shift toward smaller, lower-power cars. The potential for increased fuel economy levels through changes in buyer preferences is examined in chapter 8.

Tables 7-12 and 7-13 present EEA's projections for the year-2001 domestic fleet under two scenarios: a "product plan" conceptually similar to the 1995 product plan, and a "max technology" case driven by extremely strong pressures to improve fuel economy—presumably new regulations. The product plan assumes automakers install technologies that pay for themselves in four years (the average length of ownership for a new car's first owner) assuming a 10-percent discount rate and $1.50/gallon (in 1989$) gasoline. The domestic fleet fuel economy of 32.1 mpg, import fleet fuel economy of 34.6 mpg, and total fleet fuel economy of about 32.9 mpg obtained under this plan presume current trends in fleet size distribution and performance continue until 1995 and then plateau. If gasoline prices remain at current levels and trends of increasing performance and vehicle size continue past 1995, these projections will prove overoptimistic.

The max technology plan represents a major industry shift: the 37.3 mpg domestic fleet fuel economy (about 38.3 mpg total fleet fuel economy) by 2001 is achieved by returning to 1987 levels of size distribution and performance; rapid diffusion of a range of fuel economy technologies throughout the fleet essentially regardless of cost (the technologies actually would pay for themselves in 4 years with gasoline valued at

Table 7-11—Technology Definitions

Technology	Base Technology	Comment
Front-wheel drive	Rear-wheel drive	Assumes constant interior room
Drag reduction I	15% drag reduction from 1987 base $C_D = 0.37$	Assumes drivetrain adjustment to capture benefit
4-speed automatic	3-speed automatic	Assumes no change in performance in lower 3 gears
Electronic transmission control	Mechanically controlled transmission	Assumes shift points optimized for FTP
Tires	Improved rubber formulation and design	Evolutionary improvements
Accessories	2-speed accessory drives, improved pumps, etc.	Combination of evolutionary improvements and new technology
4-cylinder/4-valve	4-cylinder/2-valve overhead cam engine	Engine downsized for constant performance
Overhead cam	Pushrod (overhead valve) engine	Engine downsized for constant performance
Roller cam follower	Sliding cam follower	Benefits up to 4% demonstrated
Low-friction rings and pistons	Low-tension rings and low-mass pistons	Includes effects of better manufacturing

SOURCE: Energy & Environmental Analysis, Inc.

Table 7-12—Potential Domestic Car Fuel Economy in 2001 Under Alternative Scenarios (does not include test adjustments)

Technology	Fuel Economy % Benefit	Product Plan		Max Technology	
		% Market Pen. 1995-01	Fuel Economy % Gain	% Market Pen. 1995-01	Fuel Economy % Gain
Weight Reduction	3.3/6.6	80	2.64	80	5.28
Drag Reduction	1.15/2.3	80	0.92	80	1.84
Intake Valve Control*	6.0	40	2.40	70	4.20
Overhead Cam Engine	3.0	30	0.90	30	0.90
6 cyl./4-valve replacing 8-cyl.	8.0	4	0.32	8	0.64
4 cyl./4-valve replacing 6-cyl.	8.0	6	0.48	12	0.96
4 cyl./4-valve replacing 4-cyl.	5.0	10	0.50	50	2.50
Multipoint Fuel Injection (over TBI)	3.0	40	1.20	40	1.20
Front-wheel Drive	0.0	5	0.50	13	1.30
5-speed Automatic Transmission**	2.5	20	0.50	40	1.00
Continuously Variable Transmission**	3.5	15	0.52	30	1.05
Advanced engine friction reduction	2.0	100	2.00	100	2.00
Electric Power Steering	1.0	5	0.05	30	0.30
Tire Improvements	0.5	100	0.50	100	0.50
Total Fuel Economy Benefit (%)			13.03*		22.67*
Unadjusted CAFE (mpg)			31.65		36.9

NOTE: Product plan scenario starts from a different 1995 base than the maximum technology scenario which holds performance and size constant at 1987 levels.

*Synergy of intake valve control with 5-speed/CVT transmissions results in a loss of 2 percent in fuel economy.

**Over 4-speed automatic transmission with Lock-up.

SOURCE: Energy & Environmental Analysis, Inc.

Table 7-13—Import Manufacturers Fuel Economy in 2001 Five Largest Japanese Manufacturers Only (does not include test adjustments)

Technology	Fuel Economy % Benefit	Product Plan		Max Technology	
		% Market Pen. 1995-01	Fuel Economy % Gain	% Market Pen. 1995-01	Fuel Economy % Gain
Weight Reduction	3.3/6.6	90	2.97	90	5.94
Drag Reduction	1.15/2.3	80	0.92	80	1.84
Intake Valve Control*	6.0	30	1.80	60	3.60
4-valve Engine	5.0	10	0.50	50	2.50
Multipoint Fuel Injection	3.0	25	0.75	25	0.75
Front-wheel Drive	10.0	0	0.00	5	0.50
5-speed Auto Transmission	2.5	6	0.15	12	0.30
Continuously Variable Transmission	3.5	26	0.91	40	1.40
Advanced Friction Reduction	2.0	100	2.00	100	2.00
Electric Power Steering	1.0	10	0.10	35	0.35
Tire Improvements	0.5	100	0.50	100	0.50
Roller Cam Followers	2.0	30	0.60	30	0.60
Total Fuel Economy Benefit (%)			11.00		19.78
2001 CAFE (mpg)			34.2		40.0

*Synergy with 5-speed automatic transmission/CVT results in 2-percent loss in fuel economy when both technologies are used in the same vehicle.

SOURCE: Energy & Environmental Analysis, Inc.

$2.50-$3.00/gallon, or in 10 years with gasoline at $1.55-$1.90/gallon);[18] and abandonment of product lines well before their normal replacement times. Alternatively, if the size-and-performance rollback were only to 1990 levels—the appropriate criterion for S.341, the Senate Energy and Natural Resource Committee's proposed energy bill—the max technology fuel economy levels would be closer to 36 mpg and 37 mpg, respectively, for the domestic and total fleet. Unless consumer demand shifts strongly to more efficient autos, the max technology plan could cause significant economic disruption to the industry, not unlike industry adjustments of the early 1980s—a period in which the domestic manufacturers experienced considerable losses.

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[18] At 10 percent discount rates.

Note that this level of fuel economy can be obtained *only* if each company improves its fuel economy up to the technological potential of its fleet. A uniform standard such as the current CAFE standard is unlikely to achieve a total fleet fuel economy this high unless legislators set the standard at levels unattainable by companies whose fuel economy potential is lower than average—most likely including Ford and General Motors.

If the marketplace itself does not change, and *if* no new technologies are available to enter the fleet by the end of the 1990s,[19] the product plan and max technology scenarios represent extremes: at one end, a future with no changes from pre-Mideast crisis trends—possibly unacceptable considering today's oil situation; and at the other end, a major disruption to industry product planning, also possibly unacceptable considering the United States' current economic woes. A practical "technological potential" under existing market conditions and using only existing technology probably lies somewhere in between. Of course, the max technology scenario would not necessarily seem extreme if buyer preferences shifted dramatically towards higher fuel economy. This possibility is examined in the next chapter.

In practical terms, what would buyers of automobiles under the EEA max technology scenario actually get? They would pay more for their vehicles, but contrary to the grim picture drawn by some critics of higher mpg standards, vehicles would perform much the same as today. Box 7-B describes changes the max technology scenario would bring to one of the most popular U.S. cars, the Ford Taurus.

EEA has also taken a more speculative look at the long-range technological potential for fuel economy improvement, estimating the fleet fuel economy impact of a number of new technologies in the year 2010. This analysis is described in detail in a recent report to the Environmental Protection Agency.[20] The analysis substitutes a series of engineering equations for fuel consumption for the less exact approach used to develop the 1995 and 2001 forecasts. EEA obtained information on advanced technologies incorporated in the analysis primarily from detailed interviews with Toyota, Honda, Nissan, and Volkswagen. The analysis builds on the year-2001 max technology case, so that fleet size and performance are similar to the 1987 fleet.

Table 7-14 provides the EEA 2010 projections for three levels of technical and marketing risk:

- Level I—technologies most automotive engineers agree are likely to be commercialized by 2010.
- Level II—technologies about which opinion is sharply divided as to benefits or commercial prospects.
- Level III—technologies considered esoteric by most, but still within the realm of possibility.[21]

Values for Levels I and II in table 7-14 reflect the basically conservative assumption that the mix of cars sold in 2010 matches the year-2000 fleet, with no consideration of specialized vehicles such as a one-seat commuter vehicle or even a very-low-performance conventional vehicle. In other words, the analysis assumes the car market does not change in any basic fashion, and that consumers still seek features such as space, luxury features and options, smooth ride, and good acceleration and handling performance.[22] The only non-conservative assumption is use of the 1987

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[19] The year-2001 analysis incorporates only those technologies currently installed on at least one commercial car model; consequently, the analysis is basically conservative. New technologies could allow similar improvements in fuel economy to occur under less extreme conditions than the "max tech," or allow even higher levels of fuel economy to occur under max tech assumptions.

[20] Energy & Environmental Analysis, *An Assessment of Potential Passenger Car Fuel Economy Objectives for 2010*, draft final report prepared for the Environmental Protection Agency, February 1991.

[21] Energy & Environmental Analysis, February 1991, op. cit.

[22] Ibid.

Box 7-B—Fleshing Out the Maximum Technology Scenario: Transforming the Ford Taurus

In describing OTA's analysis of future fuel economy potential, we have presented lists of technologies and associated fuel economy improvements. These lists and numbers do not, we believe, deliver a readily understandable picture of the likely physical results of actually enacting new fuel economy legislation. We would like to make these results more understandable by tracking the changes that would probably occur to an actual car.

We have chosen a popular, current mid-size car model to track the changes required to satisfy the maximum technology scenario for 2001. We have used the Ford Taurus, as it is safe, relatively fuel-efficient, and can seat six passengers. The analysis could have selected other comparable cars such as the Buick Century or Eagle Premier with only slightly different results. The Ford Taurus is more efficient than the average domestic car as it already incorporates an aerodynamic design, a low-friction V-6 engine with multipoint fuel injection, and a four-speed automatic transmission. Hence, the percentage increase (from a 1987 or 1990 base) in fuel economy will be somewhat lower than the average for the fleet.

The particular model used is the Taurus sedan with a 3-liter V-6 rated at 140 hp and 220 Newton-meters of torque. It can accelerate from 0 to 60 mph in 9.8 seconds and has a CAFE rating of 27.4 mpg. Our analysis of future fuel economy potential traces possible technology improvements assuming that 1) new technologies are optimized for fuel economy and 2) the 2001 vehicle has the same interior room and acceleration performance as the current vehicle.

The most significant source of fuel economy improvement is advanced engine technology. The current 3-liter V-6 is a 2-valve pushrod type design. It can be replaced by an overhead cam 2.0-liter 4-cylinder engine that has 4 valves per cylinder, a compression ratio of 10:1, and intake valve control. This engine would actually have a higher horsepower rating (145 hp) but a lower torque rating (190 Newton-meters). Torque is a better measure than horsepower of low-speed performance (e.g., around town), and to compensate for decreased torque, a higher axle ratio must be used.

Car size (both interior and exterior) is held constant, but the weight is projected to decrease from 3,090 to 2,810 pounds.[1] Part of this will be due to the engine size reduction. If the new engine is made from aluminum, engine weight alone would be reduced by 100 pounds. Another 240 pounds would be eliminated by using advanced plastics for the front fascia, the fenders, hood, etc.; using aluminum, magnesium, and high-strength steel alloys in load-bearing structural components; and redesigning structure to capture secondary benefits. The 1990 Taurus already has an airbag but the future side-impact requirements and new emission standards will add about 60 pounds to the weight. The car is assumed to meet Tier I emission standards mandated in the Clean Air Act, but not Tier II standards that may be imposed in 2003.

The hypothetical 2001 Taurus would be more aerodynamic than today's model, with a drag coefficient of 0.30 which is equal to the best of today's cars. It would use a five speed-automatic transmission electronically controlled to optimize gear shifts, and torque converter lock-up. The car would also feature improved tires with lower rolling resistance and low-friction oils in the crankcase and drivetrain. Table 7-B-1 summarizes major differences between the 1990 and hypothetical 2001 Taurus.

According to our estimates, these technologies will allow the 2001 Taurus' fuel economy to be 35.3 mpg, or a 29-percent improvement over the 1990 car. The vehicle is forecast to have nearly equal acceleration performance at low speed and slightly better performance at high speed. Physically, the car will have the same exterior and interior size, but will look sleeker due to reduced drag coefficient. We believe ride quality will be equal to or better than today's Taurus. Moreover, the 2001 car will save 470 gallons of

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[1] Ford argues that "customer-driven features" like better sound detenting and more powerful air conditioning will add 60 pounds to Taurus weight by 1995 and more by 2001. (D.L. Kulp, Manager, Fuel Economy Planning and Compliance, Ford Motor Co., letter to S.E. Plotkin, OTA, June 17, 1991). OTA agrees that continuation of current market trends toward increased luxury features will impede improved fuel economy.

Continued on next page

fuel over 50,000 miles, assuming on-road mpg is 15-percent lower than the EPA test mpg. Any forecast involves some degree of uncertainty, and we believe the fuel economy forecast is accurate to 0.5 MPG. It is possible that the technology changes could adversely affect drivability and maintainability, although we have no reason to suspect this.

We should note the technologies described are not the only way to attain 35.3 mpg. If, for example, the two-stroke engine is commercialized by 2001, the car may attain an even higher level of fuel economy in 2001 at lower cost.

The changes described in table 7-13 will not be easily made by 2001. The 2001 car as described will require completely new designs for the body, engine, and transmission, all involving substantial capital investment. On a discounted cash-flow basis, gasoline must cost over $2.00 per gallon for the consumer to recoup the increased first cost of the car over 50,000 miles. Hence, fuel economy improvements made to the Taurus will not be cost-effective to the buyer if gasoline sells at much lower than $2.00 per gallon.

The contemplated schedule will also adversely affect the manufacturer's ability to recoup his capital investment on the preceding Taurus model. The industry operates on a product cycle of at least eight years and the Taurus was first introduced in 1986. Industry analysts expect Ford to introduce a new-model Taurus in 1994/5, and the product cycle suggests that the next model will be introduced in 2002/3. It is too late to influence the new model planned for 1994/5; under normal circumstances Ford could introduce the car forecast under a maximum technology scenario only in 2002 or 2003. Forced to introduce on or before 2001, Ford will lose 2 to 3 years of product life, which will result in significant lost revenues for Ford. Since the capital investment is amortized over an expected sales volume, reduced product life will negatively impact Ford profits. The current 5-year lead time and 8-year product cycle suggest that 2005 is a better target year if legislation requiring the complete redesign of all products is considered.

It is important to be aware of these factors when considering mpg targets defined by a maximum technology scenario.

Table 7-B-1 — Comparison of Vehicle Technologies in 1990 and 2001

	1990 Ford Taurus	Hypothetical 2001 Taurus
Weight	3,090	2,810
Interior volume (cu. ft.) (passenger + cargo)	100 + 17	100 + 17
Drag coefficient	0.33	0.30
Engine size	3.0-liter V-6	2.0-liter I1-4
Valve train	2-valve/ pushrod	4 valve/ DOHC with variable value timing
Compression ratio	9.3	10.0
Power	140 hp	145 hp
Torque	220 Nm	190 Nm
Transmission (automatic)	4-speed with lock-up	5-speed with electronic control and lock-up
0-60 mph time	9.8 sec	10.0 sec
Fuel economy (EPA Composite) a "maximum technology" scenario	27.4 mpg	35.3 mpg

SOURCE: Energy & Environmental Analysis, Inc.

Table 7-14 — Fleet Fuel Economy in 2010 at Different Risk Levels

Class	Mix*	Level I	Level II	Level III**
Minicompact	3.3	68.5	83.4	110.0
Subcompact	26.5	51.5	63.4	86.6
Sports	7.3	39.7	47.8	68.9
Compact	23.2	46.4	57.0	74.0
Intermediate	22.4	42.2	51.3	69.7
Large	6.1	39.9	48.6	65.8
Luxury	11.2	37.2	46.2	62.1
Fleet	100.0	44.8	54.9	74.1

NOTE: This table assumes no new emission standards are legislated in the post 2000 timeframe. Additionally, the table holds vehicle attributes constant at 1988 levels, except for Risk Level III.

* Unchanged from 2001 estimate.

** Based on (fossil fuel + fossil equivalent) mpg.

SOURCE: Energy & Environmental Analysis, Inc.

baseline for fleet size and performance, which implicitly assumes a moderate reduction from 1991 size-and-performance levels rather than the currently expected gradual increase in these attributes. This assumption is important—the fuel economy "penalty" associated with a continuation of trends to higher-power, larger, and more luxurious vehicles, as opposed to a reduction to 1987 levels of these attributes, is at least a few mpg in fleet fuel economy.

Tables 7-15 and 7-16 present, respectively, the basic assumptions on technologies for risk levels I and II, and a brief description of technologies included in all three levels.

The results presented in table 7-14 show that, given enough lead time and assuming successful diffusion of new technologies into the fleet, very high levels of fleet fuel economy can be reached without drastic shifts in size and performance often claimed as inevitable with such levels. For example, even using only technologies widely considered as high-probability candidates for commercialization after the turn of the century, a fleet fuel economy of 45 mpg can be achieved. Levels as high as 55 mpg can be reached without important changes in consumer attributes if certain medium-risk technologies can be moved into the fleet. And a fleet average of 75 mpg may eventually be feasible as well, though with *both* important technological advances and important changes in consumer preferences.

LEDBETTER/ROSS ANALYSIS

Marc Ledbetter of the American Council for an Energy-Efficient Economy and Marc Ross of the University of Michigan have estimated potential U.S. new car fleet efficiency for the year 2000 by using a variation of the EEA approach.[23] Ledbetter/Ross uses EEA fuel economy improvement estimates for individual technologies but alters the EEA analysis by:

- using a 7-percent discount rate rather than 10 percent as does EEA;
- calculating fuel savings over a 10-year estimated useful life; EEA's base case uses a 4-year fuel payback to simulate the average use by the first owner, but a 10-year payback for "max technology" cases;
- assuming a $1.37/gallon gasoline price;
- multiplying individual fuel economy percentage increases rather than adding them as does EEA; and
- for a specialized case, adding two technologies not on EEA's list of available technologies.

Ledbetter/Ross concludes new car fuel economy could be improved to 40.1 mpg by 2000, at an

Table 7-15—Assumptions on Technologies at Different Risk Levels for the Year 2010 (relative to baseline)

	Level I	Level II
Weight reduction	18% weight reduction on all cars	25% weight reduction on all cars
Drag reduction	C_D = 0.24 for all cars	C_D = 0.20 for all cars
Frontal area reduction	0	0 for minicompact to 5 for large/luxury
Improved packaging	0 for minicompact to 5 for large/luxury	3 for minicompact to 8 for large/luxury
Engine friction reduction	As per table 7-16	As per table 7-16
Pumping loss reduction	45%	66%
Thermal efficiency improvement	5.3%	6.87%
Rolling resistance reduction	15%	25%
Diesel engine market penetration	0	20% of mini, sub, and compact classes

SOURCE: Energy & Environmental Analysis, Inc.

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[23] M. Ledbetter and M. Ross, *Supply Curves of Conserved Energy for Automobiles*, report prepared for the Lawrence Berkeley Laboratory, March 1990.

Table 7-16—Fuel Economy Technologies at Different Risk Levels for the Year 2010

Level I
- Improved packaging efficiency
- Extensive use of aluminum and Fiberglas-reinforced plastics
- Advanced tires, reduction of rolling resistance coefficient to 0.0075
- Engine friction reduction (ceramic valves/titanium springs, two-ring pistons, 5-valve per cylinder engines, fiber-reinforced magnesium pistons and connecting rods)
- Increased compression ratio to 11

Level II
- All Level I technologies plus:
- Extensive use of graphite-reinforced plastics
- Advanced engines - *either* modulated displacement or lean burn or direct injection stratified charge 2-stroke, for smaller cars (to assure NO_x emission compliance)

Level III
- Level I and II technologies plus:
- All vehicles use turbocharged direct injection diesels
- Diesel/electric hybrid drive

SOURCE: Energy & Environmental Analysis, Inc.

average cost of $.52/gallon saved, if average automobile interior volume and acceleration performance were reduced to 1987 levels. Two technologies that would change driving "feel"—aggressive transmission management and idle-off—would increase the fleet average to 43.8 mpg at virtually the same cost/gallon saved.

WHO IS RIGHT?

Substantial differences among the various estimates of fuel economy potential present policymakers with a significant dilemma: which analysis should serve as a starting point for making fuel economy policy. Examining the available estimates as well as evaluating the nature of projecting fuel economy potential convinces us that Congress cannot expect a technical analysis to deliver a fuel economy estimate that truly represents a "correct" value of industry potential. The reasons for this are:

1. There is a subjective component to all fuel economy projections, especially regarding the level of penetration of technologies.
2. Technology costs cannot be estimated without ambiguity because industry accounting traditionally involves some models subsidizing others; also, most (perhaps all) technologies affecting fuel economy affect other vehicle attributes as well, further complicating estimates of specific costs of improving fuel economy.
3. Fuel economy estimates are extremely sensitive to policy assumptions about appropriate risk levels, and to the proper role of nonconsumer (societal) costs in determining technology acceptability, and so forth, as well as to economic and market assumptions about consumer preferences, oil prices, etc.

A further problem is that the subjective nature of parts of the projection process (particularly estimating technology penetration), the lack of a publicly-accessible data base for automotive technologies, and the paucity of academic research on fuel economy during the past decade conspire to make adequate review of a particular estimate or set of estimates extremely difficult.

For this study, OTA has examined the various estimates of fuel economy potential; attended a meeting of industry engineers, EEA, the Departments of Energy and Transportation, and the Environmental Protection Agency, during which the industry and EEA methodologies and results were presented and debated extensively[24]; attended the 1990 Society of Automotive Engineers annual government-industry meeting where industry and EEA estimates were again presented and debated; and examined several reviews of the estimates. Based on this, **we conclude that the EEA analysis, modified recently to reflect new information provided by automakers, represents the best available basis for decisionmaking about fuel economy policy. However, we note that the EEA analysis must be used in context: each individual estimate of fuel economy potential for a particular scenario is associated with a set of critical assumptions that is a powerful determi-**

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[24] Held Jan. 17, 1990, at Ford Motor Co. World Headquarters, Dearborn, MI.

nant of the magnitude of the reported fuel economy values. The estimates have little value if used without understanding their associated assumptions.

The scenarios contain some assumptions that may be viewed as conservative, and others as optimistic. For example, in its 1995 and 2001 analyses, EEA includes only those technologies already in commercial production. To the extent that new fuel economy technologies might enter the fleet, especially by 2001, the EEA estimates of fuel economy potential will be conservative. Further, EEA has not included the potential for strong market penetration by advanced diesels, because diesels have not done well in the recent U.S. market. To the extent that diesels could overcome market resistance and emissions problems, fleet fuel economy could benefit. On the other hand, some EEA scenarios assume a strong increase in oil prices, early retirement of model lines (despite likely shortfall in cost recovery), adoption of technologies irrespective of cost-effectiveness, and rollbacks in vehicle performance, size, and luxury equipment, all of which may be viewed as quite optimistic from the standpoint of maximizing fuel economy potential. To the extent that policymakers do not agree with these assumptions, they must adjust the fuel economy projections associated with them upward or downward, or rely on alternative scenarios with more agreeable assumptions.

The strongest direct challenge to EEA methodology has come from domestic automakers. As discussed earlier, the automakers' estimates of fuel economy potential are much lower than corresponding EEA estimates. For 1995, the automakers' estimates for the potential percentage increases in fuel economy are about four-tenths of EEA estimates; for 2000, depending on the scenario, the industry estimates range from less than one-third to about one-half EEA estimates. Consequently, the three automakers have rejected EEA's analysis. Briefly, the automakers claim the EEA analysis:

- fails to consider synergism between technologies;
- relies on a few empirical studies rather than basic physical and thermodynamic laws;
- ignores investment, lead time, and market-demand issues;
- counts benefits from certain technologies once as individual subsystems and then inadvertently counts them again as part of an overall separately identified system improvement; and
- estimates benefits inaccurately for actual models where the fuel economy technologies have been applied.[25]

In some instances, the automakers appear to have misunderstood EEA's methodology and technology descriptions. EEA's methodology does consider synergism between technologies, takes investment, lead time, and marketing issues into account (though probably not as manufacturers would), and has not counted twice as charged. On some technologies, the automakers have chosen very narrow definitions of what technologies entail (e.g., front-wheel drive including only drivetrain efficiency effects); in doing so, the automakers' own analyses omit potential fuel economy improvements, because they include *only* the (narrowly interpreted) EEA set of technologies. Further, part of the difference between the automakers' results and EEA's results are differences in baseline years—EEA used 1987 in the analyses examined by the automakers; the automakers chose 1989, which has higher average weight and performance than the earlier fleet. Finally, we do not believe that the automakers have uniformly applied the required assumption of constant performance and interior volume to their *own* analyses, thereby forgoing some potential fuel economy benefits of the technologies.

An important point of disagreement between EEA and the automakers is the EEA assumption that the average technology application in 1995 will be better than the average application in 1987; the automakers appear to assume technology performance will not improve over this timeframe. Another area of disagreement, discussed in box 7-A, is the extent to which automotive design can compensate for changes in driving "feel"—for example, a vehicle's ability to accelerate briskly without the necessity of flooring the accelerator pedal and attaining very high engine speeds—without reducing customer satisfaction. This disagreement can translate into differences in the degree of engine downsizing considered acceptable.

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[25] Workshop package distributed by Ford at industry/government/EEA review meeting held at Ford Motor Co. World Headquarters, Dearborn, MI, Jan. 17, 1990.

As discussed earlier, in addition to their engineering analyses, domestic automakers have produced or sponsored statistical analyses of U.S. fleet fuel economy. The use of statistical models raises troubling issues:

1. The current fleet contains vehicles and technology applications *significantly* inferior to the fleet average. The automobile industry's general direction toward fewer companies and more uniform technological and design capabilities implies that these inferior outliers bear little relationship to future technical capabilities—yet they are included in the data set.

2. Most fuel economy technology applications can be used for either fuel economy improvement or performance improvement, or a combination of the two. Generally, automakers prefer maximizing performance, because most of today's consumers strongly favor performance over fuel economy. When technologies are optimized for performance, adjustments to calculate fuel economy improvement potential from the technologies will not account for this optimization.

3. Even if a statistical model avoids normal pitfalls associated with attempting to model fuel economy improvements by searching for statistical correlations among strongly interdependent variables, *at best* it can predict the *current* fuel economy benefits associated with particular technologies. However, using such models for projection assumes that the average fuel economy benefits obtained in the fleet during the baseline year—probably 1989 or 1990—will apply to the predictive year, 1995 or 2001 in current analyses. It is almost certain, however, that 1995 or 2001 technology designs will reflect significant learning over the earlier fleets, as well as manufacturers copying from the best examples of the technologies, with one possible result being that better-than-average outliers in the 1989-90 fleet might represent the 1995 or 2001 average. Unfortunately, some outliers were discarded from the data series used by the industry-sponsored statistical analyses.

4. Construction of useful statistical models demands not searching for correlations among variables, but a technical foundation of cause and effect. Although some engineering judgment was used to create some of this foundation in one of the two models, it was supplied by the industry itself rather than independent sources.

Aside from these general issues associated with statistical analysis of future fuel economy, the methodologies used by BSA and Bussmann raise further issues.

First, BSA assumes that using the judgment of engineers from their sponsoring organization (Ford Motor Co.) is legitimate because of the indirect nature of the questions BSA posed. The validity of this assumption is unclear, and using the expertise of the sponsoring organization in this manner is, at best, quite risky for the objectivity of the analysis. Further, there is some potential that engineers may be influenced by the basic design and performance philosophy imposed by their company. For example, U.S. companies may deem it critical that shift smoothness or avoidance of high engine speeds be maintained even though maintenance of these and other conditions can affect fuel economy potential, and despite evidence that such conditions could be relaxed under the right circumstances.

Second, BSA adopted a log model because of the supposed multiplicative nature of the separate fuel economy effects of each variable. However, several factors affecting fuel economy do so in an additive, not multiplicative, fashion—e.g., rolling resistance, weight, aerodynamic drag, and accessory energy consumption.[26] Consequently, the form of the model adopted by BSA does not represent a good physical model of fuel economy dependence on vehicle attributes.

Third, BSA eliminated about half the available non-duplicative data points in the EPA data set because they were, in some sense, outliers.[27] The outliers included vehicles powered by rotary or diesel engines; police cars; vehicles with technologies that have only a few observations (5-speed automatics, turbochargers); and vehicles judged exotic and which did not fit the correlation coefficients of the model constructed without them in the data base. The implication of the need to drop so much data is that shifts in design can readily pull a vehicle away from the modeled results. This further implies that the modeled technology effects may not represent the true potential of the technologies, but simply the central tendency at the current time and for that partial group of vehicles used to create the model. This point offers strong support to point 3 above.

The Bussmann analysis apparently makes no attempt to correct for changes in performance and interior volume necessary if the fuel economy effect were measured using criteria of constant performance and interior volume inherent in the EEA estimates to which they are compared. For example, the analysis evaluates weight reduction at constant engine displacement and an increasing horsepower/weight ratio, whereas the appropriate evaluation would downsize the engine and keep horsepower/weight approximately constant.[28] Errors such as this can have a large impact on fuel economy estimates—a 10-percent weight reduction at constant engine displacement will produce about a 4-percent gain in measured fuel economy, whereas the same weight reduction at constant *performance*, with a smaller engine, will yield more than a 6-percent gain in fuel economy. Other problems include an important mistake in the grouping of automatic transmission improvements,[29] engine groupings that mix different engine types and cannot evaluate the benefits of individual technologies, and some internally inconsistent results that differ severely from Chrysler's engineering analysis.

Except for a small change in methodology and the addition of two technologies, the Ledbetter/Ross study is basically an application of EEA methodology to a more conservation-oriented scenario. The basic idea of exercising the EEA model with policy-oriented input assumptions is both sound and valuable, and OTA has adopted this approach in developing the scenario described in the next section. However, the Ledbetter/Ross study raises important concerns.

First, the methodological change—multiplying, rather than adding, individual fuel economy improvements—is theoretically incorrect. Although some fuel economy improvements may be multiplicative, others are not, including reductions in rolling resistance, weight reduction, improved aerodynamics, and improved accessory efficiency.[30] EEA chose to be conservative by adding the individual effects, and, to conservation-oriented reviewers, this may be overly conservative. The difference in the two approaches leads the Ledbetter/Ross method to yield somewhat higher results. It would also yield higher results than a hybrid method combining additive and multiplicative terms according to the nature of the technologies.

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[26] Energy & Environmental Analysis, February 1991, op. cit.

[27] D.L. Greene, Oak Ridge National Laboratory, letter to J.O. Berger et al., University of Michigan, Ann Arbor, MI, Aug. 7, 1990.

[28] Except for technologies for which changes in the torque curve do not match changes in the horsepower curve (e.g., 4-valve-perc-ylinder engines).

[29] The appropriate comparison is a 4-speed transmission with lock-up versus a 3-speed transmission with lock-up; Bussmann compares the combination of 4-speed and 3-speed lock-up transmissions to a 3speed without lock-up.

[30] Energy & Environmental Analysis, February 1991, op. cit.

Second, the scenario may be more severe than many policymakers are comfortable with, though this judgment must await policymakers' review. In devising their conservation-oriented scenario, Ledbetter/Ross builds on the rates of technology penetration in the EEA "max technology" scenario, which EEA has openly characterized as an extreme case that represents "a heavy burden of retooling for the industry and would require unprecedented and risky changes to every product sold."[31] Even assuming costs do not rise with the rapidity of retooling necessitated and ignoring the impact on the industry of not recovering initial capital investment on models retired early, EEA has calculated that the max technology case would not be cost-effective (for a 10-percent discount rate, versus Ledbetter/Ross's 7 percent) until gasoline prices reached $2.50-$3.00/gallon for a 4-year payback and $1.50-$1.90/gallon for a 10-year payback.

Third, Ledbetter/Ross may be overstating the probable effects of the two technologies they added. The effects of aggressive transmission management are unclear; and idle-off does not work well with gasoline engines and is not included in future plans of even the company (Volkswagen) that initiated it.[32]

The remaining estimates are a series of assertions by various conservation groups about the ability of the U.S. fleet to reach fuel economy level/s of 45 mpg or higher in a relatively short time.

To the extent these estimates are based, at least in part, on drastic changes in buyer preferences and fleet composition, these groups are right. As we show in chapter 8, changes in consumer preferences that result in movement toward the most fuel-efficient car in each weight or size class and in a shift toward smaller vehicles could yield large increases in the average fuel economy of the new car fleet. However, these changes are predicated on consumer acceptance of the loss in amenities—mostly interior space, acceleration capabilities, and automatic shifting—that consumers highly value, as shown by surveys and by actual vehicle purchasing patterns. Although significant shifting of consumer preference occurred during times of strong concern about gasoline availability and the potential for rationing and large future price increases, it is not clear that shifts could be achieved in the absence of pressure.

OTA believes that much of the reliance of high estimates on optimistic assumptions about new technologies and on the performance of high-efficiency vehicle prototypes is not firmly grounded. Performance projections about technologies not yet in mass production are extremely difficult—in some cases, impossible—to confirm at this time. However promising advanced technologies appear, their costs and performance will be highly uncertain until they are fully developed and in mass production and use. Similarly, the performances of "one of a kind" vehicle prototypes are instructive but far from conclusive in determining market acceptability. And we note that most high-efficiency prototypes use diesel engines, which have uncertain market acceptance and significant emissions problems in the United States. In a previous study, OTA concluded that increases in fuel efficiency to very high values "involve significant technical and economic risks," and an "increased risk that . . . insufficient development and testing will lead to poor on-the-road performance and/or product recalls."[33] In addition, OTA concluded in that study that the consumer costs of increased fuel efficiency, measured in dollars per gallon of gasoline saved, are quite speculative. For example, OTA's estimate of the consumer costs (in 1982 dollars) to achieve its 1995 new-car fuel efficiency targets varied from $.35/gallon saved to as high as $2.60/gallon saved.[34] These estimates range from economically attractive costs to costs that will be unacceptable to new-car purchasers without large increases in gasoline prices.

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[31] Energy & Environmental Analysis, *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*, draft final report prepared for Martin Marietta Energy Systems, November 1990.

[32] It is felt to be too unnerving to drivers, especially in making a left turn against traffic. Joseph Kennebeck, Director, Government Affairs, Volkswagen of America, Inc., personal communication, June 19, 1991.

[33] U.S. Congress, Office of Technology Assessment, *Increased Automobile Fuel Efficiency and Synthetic Fuels: Alternatives for Reducing Oil Imports* (Washington, DC: U.S. Government Printing Office, September 1982).

Although some elements of the EEA scenarios are distinctly optimistic, some elements of the basic EEA *methodology* will tend to yield conservative estimates of future fuel economy. These are:

1. *Multiplicative vs. additive benefits*. As noted in the discussion of the Ledbetter/Ross approach, some types of fuel economy benefits—efficiency improvements for transmissions, reductions in engine friction, improvements in engine thermodynamic and mechanical efficiency—are multiplicative, whereas EEA treats all as additive. This creates a small conservative bias.

2. *Consideration of new technologies*. The EEA projections for 1995/1996 and 2001/2002 examine only the effect of technologies currently present on at least one model in the fleet. Possibly by the mid-1990's, and certainly by 2001/2002, new technologies allowing improved fuel economy will begin to enter the fleet. Consequently, EEA projections for these years are overly conservative regarding the full array and penetration of fuel economy technologies. We note, however, that the levels of penetration of new technologies are unlikely to be high by 2001 because of lead time constraints, some imposed by automakers to guarantee reliability.

3. *Technology performance*. As discussed, in calculating the technology performance for individual technologies, EEA assumes that the better examples of fuel efficiency performance in the current fleet are likely to be reasonably representative of performance attainable by the *average* use of the technology by 2001—especially considering that many technology applications are optimized for maximum performance benefits rather than maximum fuel economy benefits. However, this shift in average performance levels is applied only to the incremental (new) use of these technologies over the intervening years. For that fraction of the fleet for which each technology is already in use, EEA does not assume any improvement in fuel economy performance levels. This is a conservative assumption.

4. *Diesel engines*. Although diesel engines provide higher fuel economy than spark ignition engines, they have not done well recently in the U.S. market and consequently have not figured in automaker planning. Also, although diesels are exempt from the 0.4 g/mi NO_x standard for automobiles until 2004, this exemption may be in jeopardy if diesels were to attain a bigger market share, and future emissions compliance is in doubt. EEA has not included diesel technology in their analyses of fuel economy potential, but large-scale penetration of diesels—especially advanced diesels such as turbocharged diesels or direct injection diesels—could increase fleet fuel economy to higher levels than possible with spark ignition (gasoline) engines.

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[34] Ibid. The cost range reflects an assumed moderate shift towards smaller cars.

Chapter 8

The Potential for Improving Fleet Fuel Economy by Changing Vehicle Buying Patterns

The fuel economy of the new car fleet is as dependent on vehicle attributes determined by consumer preference—especially, the size mix of the fleet, general performance attributes, and the prevalence of luxury features—as it is on basic vehicle design and technology. Although further improvements in vehicle design and technology can yield significant gains in fuel economy for the next 5 to 10 years, particularly if certain new technologies prove successful, very large fuel economy gains may be possible only with changes either in consumer preferences or in the availability of preferred features.

The potential effect of changes in consumer preferences can be approximated by examining what such changes could mean in the current fleet. OTA first examined this possibility in its 1982 report, *Increased Automobile Fuel Efficiency and Synthetic Fuels,*[1] reporting that the 1981 automobile fleet fuel economy could have been 33 mpg, instead of its actual 25 mpg, if consumers had consistently chosen the most efficient vehicle in each of the nine EPA size classes and producers had been able to meet demand.

More recently, the Environmental Protection Agency has conducted a similar but expanded examination of the potential effect of changed consumer preferences on the 1990 fleet.[2] Using a detailed data base for the 1990 fleet, EPA evaluated the effect on fleet fuel economy of the following shifts in consumer preference:

- auto purchasers buy only vehicles among the dozen most fuel-efficient in each weight class;
- auto purchasers buy only vehicles among the five most fuel-efficient in each weight class; and
- auto purchasers buy only the most efficient car in each weight class.

For each scenario as well as for the *actual* purchasing pattern in each weight class, EPA also examined the effect on fleet fuel economy of consumers shifting purchases towards smaller, lighter cars. For example, for the moderate weight mix shift, with average vehicle weight reduced from 3,171 pounds to 2,974 pounds (a 6.2-percent decrease), purchases of cars in the 3,500-pound class decline from 31.3 percent to 20.2 percent of all sales, and purchases of cars in the 2,250-pound class rise from 1.4 percent to 7.5 percent. For a more severe shift, with average weight reduced 11.7 percent to 2,802 pounds, cars in the 3,500-pound class go from a 31.3 percent share to 12.1 percent, and cars in the 2,250-pound class go from 1.4 to 9.6 percent. Table 8-1 presents the changes in weight class market shares for both scenarios.

EPA's analysis, results of which are presented in table 8-2, shows that changes in consumer preferences for fuel economy, performance, and vehicle size can have very large effects on fleet fuel economy. For the case of purchasing only the dozen most fuel-efficient cars in each weight class, with a 6.2-percent shift in weight class mix, the fleet fuel economy improves from 27.8 mpg to 33.2 mpg, or 20 percent. About two-thirds of the fuel economy improvement is due to consumers selecting the more efficient vehicles in each weight class, with the remainder due to the actual shift in weight class market shares. The "cost" of the improvement in terms of loss of basic con-

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[1] U.S. Congress, Office of Technology Assessment, *Increased Automobile Fuel Efficiency and Synthetic Fuel: Alternatives for Reducing Oil Imports*, OTE-E-185 (Springfield, VA: National Technical Information Service, September 1982), table 1.

[2] R.M. Heavenrich, J.D. Murrell, and K.H. Hellman, *Light-Duty Automotive Technology and Fuel Economy Trends Through 1991*, U.S. Environmental Protection Agency report EPA/AA/CTAB/91-02, May 1991.

Table 8-1—Hypothetical Shifts in Weight Class Market Shares for the 1990 U.S. Auto Fleet

Weight (lb)	1990 Weight Mix (%)	Re-mix #1 (%)	Re-mix #2 (%)
1,750	0.01	0.7	1.4
2,000	1.3	1.3	4.7
2,250	1.4	7.5	9.6
2,500	12.6	11.4	17.0
2,750	10.4	21.7	26.9
3,000	31.0	31.2	25.1
3,500	31.3	20.2	12.1
4,000	11.0	5.6	2.8
4,500	1.07	0.49	0.22
5,500	0.013	0.006	0.003
Average weight	3,171	2,974	2,802
Change from status quo (%):		-6.2	-11.7

SOURCE: U.S. Environmental Protection Agency, Ann Arbor, MI.

Table 8-2—"Best in Weight Class" Analysis, 1990 Model Cars

1990 3,171 lb average wt	Re-mix 2,972 lb average wt	Re-mix 2,802 lb average wt	Consumer Purchase
Average miles/gallon			
34.4	37.5	40.3	Best in class
32.5	34.7	36.8	Best five in class
31.2	33.2	35.3	Best dozen in class
27.8	29.6	31.5	All cars
Average cubic feet			
98	94	93	Best in class
103	99	98	Best five in class
102	99	98	Best dozen in class
107	103	100	All cars
Average 0 to 60 mph time, seconds			
14.2	15.1	15.6	Best in class
13.1	13.5	13.7	Best five in class
13.1	13.4	13.5	Best dozen in class
12.1	12.4	12.7	All cars

SOURCE: U.S. Environmental Protection Agency, Ann Arbor, MI.

sumer attributes is a 7-percent decrease in the average interior volume of the fleet (from 107 to 99 cubic feet.) an 11-percent increase in 0-to-60-mph acceleration time (12.1 to 13.4 seconds), and a general shift away from automatic transmissions. The "average car"—the car that attains the average fuel economy of the fleet—shifts from a Dodge Dynasty or Volvo 740 to a Toyota Camry.

A more extreme shift in consumer preferences will yield a significantly higher gain in fuel economy. If consumers had selected only the best model in each class and absorbed a 12-percent shift in weight classes (that is, an overall reduction in vehicle weight of 12 percent), fleet fuel economy would have been 40.3 mpg, a 45-percent improvement over the actual 27.8 mpg, with responsibility about evenly split between the shift to higher-fuel-economy models and the weight-class mix shift. The cost in consumer attributes is a 13-percent decrease in average interior volume (107 to 93 cubic feet), a 29-percent increase in 0-to-60 time (12.1 to 15.6 seconds), and, as before, a general shift from automatic to manual transmissions. The average car shifts from the Dodge Dynasty or Volvo 740 with automatic transmission to a Pontiac Lemans or Ford Escort—much smaller cars—with manual transmission.

There can be endless argument about the realism of the above scenarios given the relative stability of fleet average interior volume over time, the general rising trend in 0-to-60-mph acceleration time, and the popularity of automatic transmissions. In particular, many might question the likelihood of a massive shift away from automatic transmissions. If a change in transmission type is not allowed, the fuel economy benefits are about 60 percent of those where a large shift takes place.[3] Only a portion of the reduction in benefits is due to the transmission change alone. Some high-efficiency models such as the Honda Civic CRX HF do not have a model with automatic transmission, but have other attributes that contribute to fuel economy (in the HF's case, an efficient low-horsepower engine). These features are not available to purchasers of vehicles with automatic transmissions.

It is worth noting that most lost fuel economy could be recaptured—at a price—with advanced automatic transmissions with efficiencies close to those of a manual, for example, five-speed electronically controlled automatics with lock up in all upper gears.

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[3] John German, Certification Division, U.S.Environmental Protection Agency, Ann Arbor, MI, personal communication, June 11, 1991.

Although these shifts are not realistic as measures of what could happen *instantaneously* (they do not account for problems of expanding production capacity, for example), they do illustrate what could happen over time, perhaps 10 years—with some changes, especially those associated with selecting the dozen most efficient cars in each weight class and the moderate mix shift, happening even sooner.

Chapter 9
Designing A New Fuel Economy Bill

Policymakers who are convinced new CAFE legislation is a desirable approach to improving fleet fuel economy must confront a number of key issues. The two overriding issues are, first, how the standards should be structured, and, second, how high the target fuel economy should be. Selecting a structure for the standards may be as important as selecting the numerical target.

ESTABLISHING THE STRUCTURE OF NEW CAFE STANDARDS

The current CAFE standard assigns a goal of 27.5 mpg to every automaker regardless of the vehicles they produce. Domestic automakers have severely criticized this regulatory structure because manufacturers producing larger vehicles or a variety of vehicle sizes must meet a more demanding technological standard than manufacturers who concentrate on smaller vehicles that normally are more fuel efficient.[1] This leaves automakers who focus on small cars far more flexibility than "full line" manufacturers to introduce features that are attractive to consumers but fuel inefficient—e.g., four-wheel drive, high-performance engines, etc. Further, the fuel economy standard selected under such a structure will tend to be heavily influenced by the (relatively low) fuel economy level that can be reached by the company with the most difficult task (i.e., the largest, most powerful mix of vehicles). Since such a standard would provide little challenge to companies manufacturing primarily small vehicles, the fleetwide fuel economy level achieved will be lower than could be achieved if *all* automakers were forced to improve fuel economy to the maximum extent possible.

Another problem with the current approach involves the separation of domestic and import fleets according to the percentage of parts manufactured in the United States (the "local content"). Because the "import" fleets of the domestic automakers have high CAFE ratings (in 1990, 35.6 mpg for Ford, 37.6 mpg for General Motors'), the domestics have been able to manufacture more of some low-efficiency models' parts overseas and move those models to the import fleet—thus improving the CAFEs of their domestic fleet while leaving the import fleet's CAFEs safely within standards. Ford recently switched its Crown Victoria model to an "import" by increasing its foreign parts content to 25 percent—trading away U.S. jobs for an improvement in Ford's regulatory position vis-a-vis CAFE enforcement with no actual fuel economy improvement. On the other hand, earlier in the history of the legislation, CAFE rules forced automakers to build small cars as part of the U.S.-made fleet—with a positive effect on domestic job creation.

In spring, 1989, Senator Richard Bryan of the Consumer Subcommittee (Senate Committee on Commerce, Science, and Transportation) introduced legislation calling for all automakers to improve their companywide fuel economy levels 20 percent by 1995, and 40 percent by 2001, over levels achieved by model year 1988. This legislation sought to overcome criticism leveled at the current uniform standard by forcing all automakers to improve by the same amount. The structure called for in the legislation generally is referred to as a "uniform percentage increase." Senator Bryan has reintroduced this legislation for 1991, as S.279.

Another CAFE proposal would base each automaker's standard on the size mix of vehicles it manufactures, giving makers of small cars a higher mpg target to reflect the inherent fuel economy advantage small cars have over large cars.[2] Ideally, to meet individual mpg standards, each company would have to install about the same level of fuel economy technology as every other company. In other words, a correctly set standard would not create any market advantage or disadvantage.

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[1] Obviously, some small cars that are high-power sports models obtain relatively low fuel economy levels. However, vehicle size is a critical factor in fuel economy, and manufacturers of small vehicles generally will have an easier task than manufacturers of large vehicles in meeting the same fuel economy standard.

The standard would work as follows:

1. Each vehicle model would be assigned a fuel economy target determined by a formula *relating required fuel economy to vehicle interior volume*. (Alternatively, each vehicle size class could be given a fuel economy value, and each vehicle would then be given a target based simply on its size class.[3]) As discussed in box 9-A, interior volume must be defined carefully to allow a single standard to apply to a range of auto types, including station wagons.
2. Each company's fuel economy standard would then be calculated by taking the sales-weighted average of the various fuel economy targets assigned to all of its models. This company standard, or Volume Average Fuel Economy (VAFE) standard, could be computed at the beginning of the year, based on last year's sales mix, or at the end of the year based on actual sales.
3. It is worth noting that *each model* in an automaker's fleet would not have to meet its fuel economy target so long as the sales-weighted average of all of the maker's models achieved the assigned VAFE standard. This leaves each company the flexibility of deciding how to allocate fuel economy technology across its fleet, and further allows it to have a mix of family-oriented, commuter, and high-performance models so long as the average of their fuel economies satisfies the company standard.
4. The formula for assigning fuel economy targets can be established by the government

Box 9-A—Measuring Interior Volume for Application to a Volume-Based Standard

An examination of how fuel economy varies with vehicle interior volume shows that the simplest measure of volume (all available space within the automobile) is not the best measure for use with a fuel economy standard based on interior volume. Figure 9-A-1 shows how the average fuel consumption of different classes of automobiles varies with total interior volume. The figure demonstrates that the fuel consumption rates of subcompact through large sedans form a straight line on the graph; all station wagons fall on a different straight line. Minicompacts and two-seaters fall outside these lines, generally having high fuel consumption for their interior space compared to other classes—not surprising because most cars in these two categories are basically sports cars and have high power-to-weight ratios.

The fuel consumption/interior volume relationships for sedans and wagons tend to converge toward a single line on the graph if interior volume measurements for the wagon class do not give full "credit" to the added cargo volume in wagons. Using this more restricted definition of interior volume, it should be possible to design a single interior-volume-based fuel economy standard applicable to all sedans and wagons *except sports cars* that approaches the goal of creating a uniform technological challenge regardless of car size.

If Congress chooses this approach, it must decide how to deal with minicompacts and two-seaters, since these classes would tend to have great difficulty in attaining target fuel economy levels based on their (low) interior volumes. Companies focusing on these classes are likely to find it impossible to meet their company standards unless these classes are treated differently than the rest of the fleet. This would impose penalties on these classes, raising their purchase price and presumably lowering demand. Congress might be comfortable with such a result, but if not, it must allow separate treatment for these vehicles.

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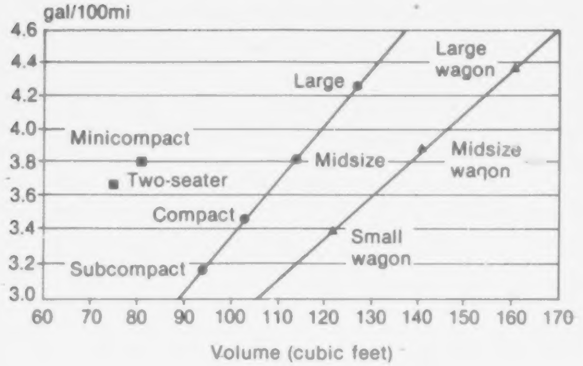
[2] OTA discussed this CAFE structure in its May 2, 1991, testimony to the Consumer Subcommittee. Also, Barry McNutt of the Department of Energy discussed interior-volume-based standards and size-class standards in a May 1985 talk.

[3] This formulation has the disadvantage of providing an incentive for automakers to enlarge models at the upper limits of any size class to move them to the next higher class.

Figure 9-A-1—Fuel Consumption and Volume, 1990 Sedans and Wagons



SOURCE: U.S. Environmental Protection Agency, 1991

to aim for any fleetwide average desired. The VAFE formula would have to be based on extrapolating from the most recent data on fleetwide size distribution, so unexpected shifts in sales, for example, from larger to smaller cars, would result in the fleet attaining a fuel economy level slightly different than predicted. Differences would not be large unless large shifts in sales occurred.

Both Senator Bryan's "uniform percentage increase" and an "interior-volume-based—VAFE-standard" represent improvements over the current CAFE approach because they account for differences in fleet makeup among the various automakers. Simpler in concept, the Bryan approach is easier to understand and explain. However, it makes no allowance for differences in the degree to which automakers have applied fuel economy technology. To the extent that some automakers may have used a higher level of technology during the proposed base year, this approach penalizes them with a more difficult mpg target than other automakers with fleets similar in size mix but who used inferior efficiency technology (see box 9-B). In doing so, it rewards companies that have made less effort thus far, since these have the most technological "headroom" to improve their fuel economies. Furthermore, assigning standards based on company fuel economies achieved years earlier will make it difficult for automakers to shift sales strategies unless these shifts are toward a fleet with smaller vehicles. This will tend to discourage Japanese automakers from pursuing their current strategy of competing in the luxury and larger-car markets. In other words, the proposed legislation may be viewed as anticompetitive.

Some of the tendency of the "uniform percentage increase" approach to reward companies that have low baseline fuel economies and penalize companies with high baselines can be mitigated by placing floors and caps on the company requirements—i.e., by demanding that companies achieve a minimum level of fuel economy regardless of baseline value, and placing an upper limit on the company standard, even if its baseline value is very high. S.279 places a floor of 27.5 mpg and a cap of 40 mpg for 1996, and a floor of 33 mpg and cap of 45 mpg for 2001. This means that for 1996, companies with baseline fuel economies below 22.9 mpg must attain a percentage increase higher than 20 percent to achieve their target fuel economy, and companies with baselines above 33.3 mpg will need increases less than 20 percent. For 2001, the baseline floor and cap breakpoints are 23.6 mpg and 32.1 mpg, respectively. This means companies such as Isuzu (34.9 mpg in 1988[4]), Suzuki (50.3 mpg) and Hyundai (35.0 mpg), as well as domestic import fleets (Ford obtained 35.6 mpg in 1988, General Motors, 37.6 mpg), will not be required to improve the full 20 and 40 percent by 1996 and 2001. However, neither Toyota (32.6 mpg) nor Honda (32.0 mpg), companies with superior fuel economy performances in 1988 even accounting for their size mix, really benefit from the cap.

A uniform percentage increase approach, because it is based on past relationships, must take special care in dealing with new market entrants with no "baseline" fuel economy values. If new entrants are treated more leniently than established automakers, the latter may form new com-

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[4] Fleet fuel economy values from U.S. Department of Transportation, National Highway Traffic Safety Administration, "Summary of Fuel Economy Performance 1988," U.S. DOT/NHTSA NEF-31.

Box 9-B—What Accounts for the Difference in CAFE Among Different Automakers?

The fairness of a fuel economy standard demanding that each automaker attain a uniform percentage increase over its fleet fuel economy in a base year depends in part on the extent to which some automakers might have done very much more (or less) than the average in making their fleets efficient in that year. To the extent that an automaker may have installed more fuel efficiency technology, or used more fuel efficient design than the average, he would, in effect, be penalized by having a more stringent target to meet with less technological "headroom" than available to the average automaker. Similarly, a less-efficient-than-average automaker would be rewarded with a lower target and greater degree of technological headroom.

One way of measuring design and technology efficiency of different corporate fleets is to remove the effect of differing vehicle size mixes from each company's CAFE value. To do this, OTA devised a set of company-by-company size-class-mix-weighted standards to reach *actual* fleet new-car fuel economy in 1988—28.3 mpg—and compared these standards to the manufacturers' achieved fuel economies. Where achieved values were above, below, or the same as the standards, the manufacturers' cars were better than, worse than, or the same as the industry average fuel economy adjusted to account for the sales mix of the fleet.

Figure 9-B-1 compares the company-by-company targets with the actual fuel economy values achieved in 1988. The figure shows that two U.S. companies are within 1 percent of their targets; that is, their fleet fuel economies are near the industry average *taking into account the size class mix of their fleets*. Half of the Japanese companies are well over the industry average, with the other half at or near the average. The European company is considerably below the average.

This comparison shows that ***differences in the size class mix of domestic and import fleets account for much, though not all, of the differences in the fuel economies of these fleets***. For example, of an 18-percent difference in the fuel economy levels between often-compared U.S. and Japanese manufacturers (General Motors and Toyota), approximately 12 percent—two-thirds—is explained by the size class mix. The remainder presumably is due to differences in technology, design, and vehicle performance.

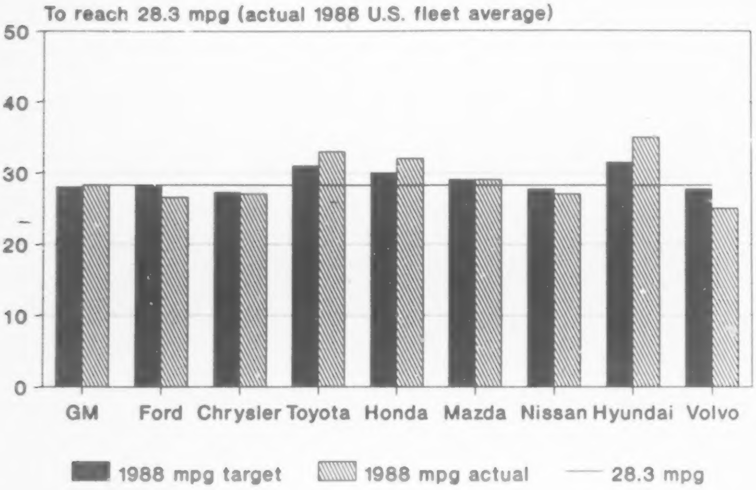
The comparison indicates that a "uniform percentage increase" standard based on a 1988 baseline—as specified in the legislation sponsored by Senator Bryan—would penalize some Japanese manufacturers, though not nearly to the extent that might be presumed from examining only the large differences between their CAFEs and those of U.S. companies. Because some Japanese companies—particularly Toyota and Nissan—have increased the size of their vehicles in the 1988-91 period relative to U.S. automakers, the disadvantage posed by this type of standard will be greater than implied by the above analysis.

panies to market their less efficient models, improving the CAFE position of the remaining models in their fleet at little cost and with no actual improvement in fuel economy.

If the volume-based or VAFE standard were determined from actual sales (i.e., standards would be computed at year-end based on that year's sales figures), automakers would have flexibility to change sales strategies without making their fuel economy targets impossibly difficult to attain. This also avoids penalizing automakers if market trends change unexpectedly, since standards would reflect changing sales figures. However, the VAFE standard's "size neutrality"—giving small cars as difficult a standard as large cars—means there is no incentive for an automaker to boost sales of small cars, a feature of the current CAFE standard and, indeed, any standard based on a formula that does not change with shifts in fleet size mix. The more that Congress might want to encourage consumers to drive smaller cars, which tend to be more fuel efficient, the less a VAFE-type standard might be favored.

The VAFE approach has been criticized because it cannot specify an exact fleet fuel economy target. Because relative sales of large and small cars may shift over time, the fleet fuel economy

Figure 9-B-1—Size-Class-Weighted Fuel Economy for 1988



SOURCE: Office of Technology Assessment, based on Oak Ridge data, 1989.

target established by VAFE standards would shift as well. If more small cars are sold, the fleet target will increase; if more large cars are sold, it will decrease. In contrast, the current uniform CAFE guarantees a fleet minimum fuel economy, assuming all automakers are in compliance.

It has been presumed that the uniform percentage increase approach to fuel economy standards will not have this problem because required increases are based on previously established company fuel economy levels, and thus each company's target fuel economy cannot change. However, the *fleet* target will change with any shifts in the market shares of the companies. If a company with a high target gains market share, the fleet target will increase, and if a company with a low target gains market share, the fleet target will decrease. Consequently, *neither* currently proposed approach to new fuel economy standards can guarantee a minimum fleet fuel economy other than the minimum for any one component of the standard—for the uniform percentage increase, the target for the least efficient company; and for the VAFE approach, the target for the largest vehicle.

Recently, Mercedes-Benz, BMW, and Porsche proposed an alternative structure for fuel economy standards that relies on several factors—the vehicle curb weight, the ratio of curb weight to interior volume, and the ration of curb weight to torque—to define allowable fuel economy levels. The proposal establishes a fuel economy baseline for each model using a formula for fuel consumption derived from a regression analysis of all EPA certified 1990 models, with the above variables as regression variables. In other words, the proposal starts with a formula of the form:

$$\text{Fuel consumption} = \text{A x curb weight} + \text{B x} \frac{\text{Curb weight}}{\text{interior volume}} + \text{C x} \frac{\text{curb weight}}{\text{torque}}$$

where A, B, and C are constants,

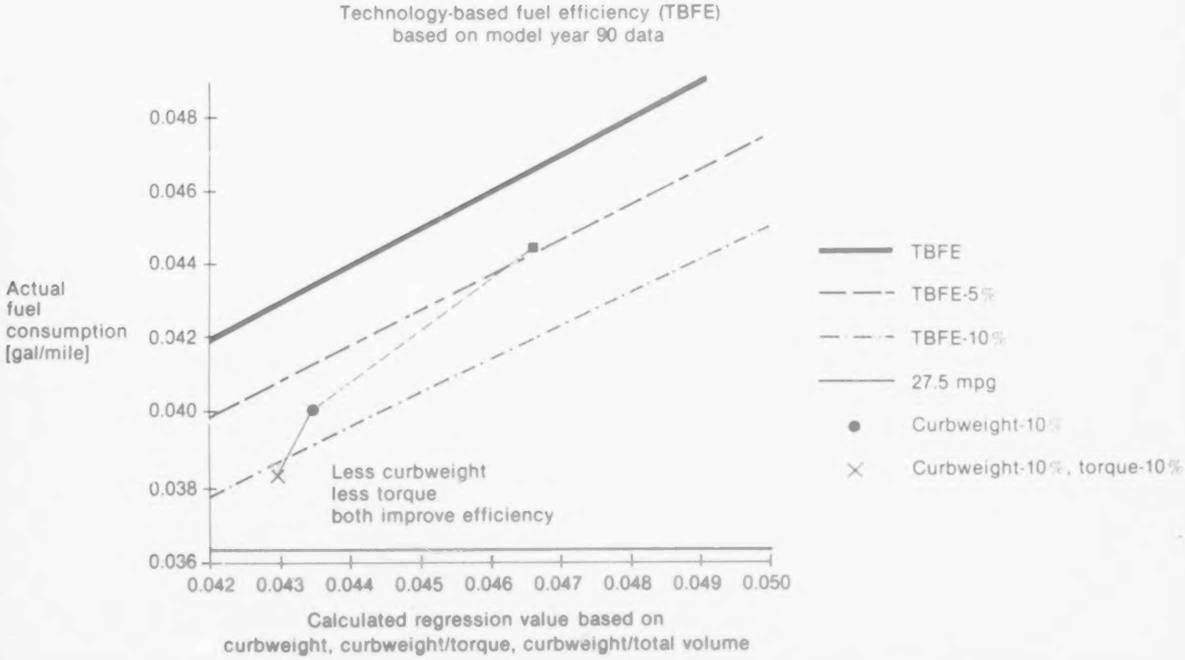
which approximately defines the fuel consumption of vehicles in the 1990 fleet. For a 20-percent improvement in fleet fuel economy, new vehicles have to achieve a fuel consumption level 20-percent lower than given by the formula *using the new values of curb weight, interior volume, and torque*. If these values do not change from their 1990 levels, the vehicles must simply attain a 20-percent reduction in fuel consumption.

This system has the advantage of allowing companies that compete in niche markets to satisfy fuel economy standards by improving technology without abandoning its niche or being forced to add model lines of lighter or lower-power vehicles, as would be the case with other proposed standards. The system also demands technology improvements: simply adding a model line of small cars *of the same design and technology level* will not help; the formula will demand the same kind of efficiency improvement from that model as well.

The system has some interesting characteristics. Most important, although increasing a vehicle's torque and weight while holding its interior volume constant will allow the vehicle to be subject to a higher allowable fuel consumption standard, basing the new allowable fuel economy on the regression equation implies that the allowable level will be *technically* more difficult to meet. In other words, there is a positive incentive to reduce weight and torque while holding interior volume constant, because it will be easier to meet the allowable fuel consumption level. This is illustrated by figure 9-1. This incentive is important, because high fleet fuel economy levels will be difficult to meet unless the "horsepower race" is ended and unless weight reduction measures continue.

Second (and less favorable to this system's likely attractiveness to Congress), it allows a vehicle that is more powerful than another but otherwise identical to meet a lower fuel economy standard.[5] This may be difficult for a Member of Congress to

Figure 9-1 – Change in Level of Compliance With the Type of Fuel Economy Standard Proposed by Mercedes-Benz, BMW, and Porsche if Curbweight and Torque Are Reduced



The square on the graph represents an automobile with a fuel economy level about 5-percent higher than the average automobile of the same weight, interior space, and torque. If the auto's designers reduce its weight by 10 percent through design changes and material substitution, the auto will reach a fuel economy level significantly in excess of 5 percent better than the average for a vehicle with its new weight/space/torque combination, as shown by the dotted line. Lowering torque by 10 percent (represented by the solid line between the circle and cross) will allow the auto to improve still further, to greater than 10-percent higher fuel economy than average.

SOURCE: Mercedes-Benz of North America, Inc., 1991.

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[5] Though, as noted, the lower standard will be technically more difficult to meet than the standard applied to the lower-power car.

explain to constituents. And third, this system cannot "guarantee" meeting a particular fleet fuel economy level because, like size-based standards, changes in vehicle characteristics (here, weight and performance particularly) will change the magnitude of the standards. Nevertheless, in our view the proposed system is worth further investigation.

DEFINING A FUEL ECONOMY TARGET

Selection of the numerical fleet fuel economy target demands consideration of the following issues:

- Whose analysis of fuel economy potential is to be believed? For that analysis, what assumptions are appropriate for a public policy analysis? And how can the results of that analysis be appropriately translated into an actual target for a fuel economy regulation?
- How should consumer preferences for vehicle size, luxury characteristics, and performance be taken into account in setting a target? In other words, to what extent is Congress willing to demand levels of fuel economy that may require changes in the makeup of the light-duty fleet that might displease consumers? (Or, to what extent is Congress willing to take measures, such as increased gasoline taxes, or vehicle taxes and rebates tied to efficiency levels, that could stimulate changes in consumer preferences?)
- What are the possibilities for new technologies, and how should the uncertainty inherent in projecting the likely success and performance of new technologies be taken into account in standard setting? Should a future fuel economy standard be "technology forcing" in nature?
- How much economic pressure on the industry is reasonable given the importance of reducing U.S. oil consumption, the financial strains on certain companies, and the importance of domestic auto production to the U.S. economy?
- What might the safety effects of new standards be, and how should these effects be taken into account in setting a standard?

SELECTING AND APPLYING AN ANALYSIS OF FUEL ECONOMY POTENTIAL

As discussed in chapter 7, OTA believes the fuel economy analyses performed by Energy & Environmental Analysis, Inc., as modified after discussions with domestic and foreign auto manufacturers, represent the most credible of the available analyses. In our view, the analyses presented by several conservation groups lack an appropriate analytical foundation and, for the 1996 to 2002 timeframe, rely too heavily on unproven technologies; and those of the automakers are skewed toward low fuel economy values by the imposition of assumptions not compatible with a strong regulatory push to higher fuel efficiency.

EEA's previous scenarios for future fuel economy represent two extremes—the "product plan" case represents a guess at a future with no additional regulatory pressures on fuel economy levels and limited economic pressures; the "max technology" case represents a relatively unrealistic scenario imposing "a heavy burden of retooling for the industry and would require unprecedented and risky changes to every product sold."[6] In reality, however, the product plan for 2001 may be considered optimistic, because it assumes an increase in oil (and gasoline) prices, whereas many analysts believe oil prices can remain flat over this timeframe—and because it assumes that post-1995 technological additions will be designed to maximize fuel economy rather than to improve performance. In other words, OTA considers it quite plausible that fleet fuel economy levels could be well below the product plan level of 33 mpg in 2001—though we believe it unlikely that they might remain at today's 28-mpg level.

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[6] Energy & Environmental Analysis, Inc., *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*, draft final report prepared for Martin Marietta Energy Systems, November 1990.

As discussed previously, OTA's product plan projection for 1995 is 29.2 mpg for the fleet. How much higher could fleet fuel economy be pushed? There is not a great deal of time between now and 1995 for manufacturers to make important changes to their product plans. EEA has not developed a "maximum technology" plan—a scenario that assumes much greater penetration of fuel economy technologies—for the 1995 date, because it feels significant increases in technology penetration are not realistic for this early date. However, the companies are not without some degree of flexibility in this timeframe, since they must be prepared to respond to rapid changes in consumer preferences or unforeseen consumer responses to new products. Further, the fuel economy penalty associated with new emission and safety standards will depend somewhat on market and regulatory pressures to improve fuel economy; the penalty need not be as high as estimated by EEA (nearly 3 percent) for "business as usual." Consequently, we believe Congress could realistically set a 1995 fuel economy goal for the total U.S. fleet somewhat higher than the EEA "product plan" value of 29.2 mpg. Further, companies can achieve fuel economy credits for producing alternative-fuel vehicles, so they can raise their official CAFEs by over 1 mpg by producing large numbers of these vehicles.

OTA concludes Congress could realistically set a fuel economy goal for the 1995 model year of 30.0 mpg for the total fleet, to be achieved by some combination of expected increases in penetration of fuel economy technologies coupled with reductions in expected vehicle performance increases and compliance with emissions and safety standards with minimum losses in fuel economy. The companies could also produce alternative-fuel vehicles to reach the goal, though the fleet then would not physically attain the full 30 mpg. If Congress includes the potential to manufacture altfuel vehicles in setting the standard, the standard could be raised to about 31 mpg—but this would transform the alternative-fuel credit from an *incentive* to produce these vehicles to a virtual *requirement*.[7]

This level of fuel economy can be obtained only if each company is required to improve its fuel economy according to the technological potential of its fleet; a uniform standard such as the current CAFE-type standard cannot achieve a total fleet fuel economy this high, since, to be politically acceptable, it will likely have to accommodate the fuel economy achievable by the major domestic companies, whose potential is lower than the above averages.[8]

For 2001, automakers have considerably more flexibility to raise their fleet fuel economy. OTA has defined a "regulation-driven" scenario for 2001 that represents an attempt to define a set of criteria for incorporating societal energy goals into vehicle design decisions. The criteria are:

1. Technologies are selected if they provide fuel savings that, with a 10-percent discount rate, will pay back extra first costs in 10 years at $2.00/gallon gasoline (high price and long payback period selected to reflect societal costs of gasoline consumption*);
2. Some allowance is made for inclusion of new technologies (not yet in the fleet) by 2001;
3. Size and performance of the 2001 fleet is rolled back to 1990 levels; and
4. Penetration rates for technologies are constrained to correspond to normal model redesign schedules, so costs are held down, sufficient time is allowed for recouping ini-

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[7] And violate the spirit of the alternative fuel credit legislation.

[8] Domestic full-line manufacturers do not, however, have the lowest potential among major manufacturers. The companies with the most difficult task are likely to be the European limited-line manufacturers producing luxury and performance vehicles.

*In other words, the $2.00/gal cost-effective price reflects the expected market price plus an additional cost representing national security, pollution, and other concerns associated with gasoline consumption.

tial capital costs of preceding models, and engineering-and-design manpower does not become a limiting factor.

Table 9-1 shows the technology-by-technology details of the OTA scenario for the domestic automobile fleet. The scenario is similar to the maximum technology scenario discussed in chapter 7 in that all technologies associated with that scenario are justified by the combination of $2.00/gallon gasoline and 10-year payback in the OTA scenario. However, the less severe conditions for the rate of technology penetration in the OTA scenario slows down these rates; the level of technology penetration achieved in 2001 by the max technology scenario is not achieved in the OTA scenario until 2005. The slowdown in the rate of technology penetration affects six technologies: weight reduction, drag reduction (improvement in aerodynamics), intake valve control, five-speed automatic transmissions, continuously variable transmissions, and four-valve engines. The details of this slowdown are explained in box 9-C. The net effect of the slowdown is to reduce the total percentage benefit (over 1995 fuel economy levels) in 2001 by 5.58 percent for domestic manufacturers. This yields a net fuel economy benefit (over a 1995 baseline assuming 1990 size and performance) of 17.09 percent versus 22.67 percent for the maximum technology scenario, with a resulting domestic fleet fuel economy of about 34.5 mpg (including a 0.4-mpg test adjustment) by 2001. A similar calculation for imports results in a 37.4-mpg average, with a total fleet fuel economy of 35.5 mpg.

As discussed in box 9-C, all body, engine, and transmission changes can be completed by 2005 within the normal lifecycle limits of these components. Consequently, by 2005, this scenario will resemble the 2001 maximum technology scenario except that weight and drag reduction can have higher levels of penetration than in max technology. Shifting weight reduction from 80 percent (max technology) to 100 percent (regulation-driven) and drag reduction from 80 percent to 90 percent[9] yields an additional 1.55-percent fuel economy benefit. This yields a domestic fuel

Table 9-1—Potential Domestic Car Fuel Economy in 2001 Under Product Plan and Regulatory Pressure Scenarios (does not include test adjustments)

	Fuel Economy Benefit	Product Plan		Regulatory Pressure	
		Market Pen. 1995-01	Fuel Economy	Market Pen. 1995-01	Fuel Economy
Weight Reduction	3.3/6.6	80	2.64	60	3.96
Drag Reduction	1.15/2.3	80	0.92	60	1.38
Intake Valve Control *	6.0	40	2.40	40	2.40
Overhead Cam Engines	3.0	30	0.90	30	0.90
6-cylinder/4-valve replacing 8-cyl	8.0	4	0.32	5	0.40
4-cylinder/4-valve replacing 6-cyl	8.0	6	0.48	7	0.56
4-cylinder/4-valve replacing 4-cyl	5.0	10	0.50	28	1.40
Multipoint fuel injection (over TBI)	3.0	40	1.20	40	1.20
Front-wheel drive	10.0	5	0.50	13	1.30
5-speed automatic transmission **	2.5	20	0.50	25	0.63
Continuously variable transmission **	3.5	15	0.52	15	0.52
Advanced engine friction reduction	2.0	100	2.00	100	2.00
Electric Power Steering	1.0	5	0.05	30	0.30
Tire Improvements	0.5	100	0.50	100	0.50
Total Fuel Economy Benefit (%)			13.03*		17.09*
Unadjusted CAFE (mpg)			31.65		34.07

NOTE: Product plan scenario starts from a different 1995 base than the regulatory pressure scenario which holds performance and size constant at 1990 levels.

* Synergy of intake valve control with 5-speed/CVT transmissions results in a loss of 2 percent in fuel economy.
** Over 4-speed auto transmission with lock-up.

SOURCE: Office of Technology Assessment, 1991, based on analysis by Energy & Environmental Analysis, Inc.

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[9] This is limited because some 1990 cars already have extremely low aero-dynamic drag coefficients.

Box 9-C—The OTA Scenario for 2001: Max Technology Without Enforced Early Retirements

OTA's "regulatory pressure" scenario for 2001 postulates that Congress wishes to incorporate the "societal costs" of gasoline—costs not included in gasoline prices, including environmental damages and national security costs—into the selection of new fuel economy standards. The scenario values gasoline at $2.00/gallon,[1] more than its expected price, and selects technologies that offer 10-year fuel savings at least as high as the added cost of the technologies. Unlike the "maximum technology" scenario, this scenario respects the normal lifecycle requirements of automobile components, allowing automakers to recover their capital costs according to usual product development and sales schedules.

The design and product development lead time is 4 to 5 years, indicating that products for the 1996 model year are now being finalized, while products for 1995 have moved to a stage where tooling orders are being placed. Mainstream products sold at high volumes (over 150,000 units per year) will have a lifecycle of 7 to 8 years prior to redesign, so the 1996 products could last to 2004.

Products with lower sales volumes (30,000 to 100,000 units per year), including sports and luxury cars or specialized "niche-market" cars, have lifecycles of 10 years. These products include Camaro/Firebird (last redesigned in 1982), the Corvette (1984), and the Cadillac Brougham (1978) for GM; the Mustang, Mark VII, and Continental for Ford; and the Dodge Daytona for Chrysler. These models account for about 6 percent of total domestic car sales, and all are well along the product replacement cycle and would not normally be redesigned again by 2001.

Assuming none of the specialty cars (with 6 percent of sales) will be redesigned by 2001 and all high-volume lines will be redesigned between 1996 and 2004, normal turnover of model lines between 1996 and 2001 will be about:

$$0.94 \times \frac{2001 - 1996}{2004 - 1996} = 0.587$$

In other words, about 60 percent of all model lines can be redesigned with material substitution and drag reduction without altering the product lifecycle of designs introduced between 1992 and 1996.

Engine and transmission redesigns must be considered separately from body redesign. Engines and transmissions typically have lifecycles of 10 years. However, most domestic OHV engines are based on very old designs which have been improved over the years, and a lifecycle concept cannot be readily applied to estimate the fraction of these engines that will be terminated during any period. Moreover, conversion of OHC engines from two- to four-valve can be accomplished by changing the cylinder head alone. However, a 100-percent conversion to four-valve will require the introduction of smaller engines, to maintain constant performance and get maximum fuel economy benefits, but the domestic industry has no track record of large-scale introduction of several new engines to replace the existing product line (Toyota did introduce four-valve engines into their entire product line from 1987-1990). In the absence of historical benchmarks to guide an estimate, we assume a penetration of 70 percent for four-valve engines without significant disruption by 2001, based on conversion of current and future OHC two-valve engines.

Transmissions have a typical lifecycle of 10 years, and a new generation of electronically controlled four-speed automatic transmissions are being introduced over the 1989-95 period. Conversion to five-speed automatics or CVTs can occur over the 1999-2005 period without disrupting the lifecycle, suggesting that only 30 percent of automatic transmissions [(2001 - 1999)/(2005 - 1999)] can be converted to five-speed automatics or CVTs. Since large car transmissions were the first converted to four-speed designs and will be the first to receive five-speeds, and CVTs can be used on small cars only, we expect five-speed automatics to dominate the 30 percent of transmissions to be converted during the 1999-2001 period. CVT penetration by 2001 should be only about 5 percent.

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[1] This value is *not* OTA's estimate of the true societal cost of gasoline. We have not attempted to estimate such a value. Also, we believe the such a value would have a large subjective component, so that individual policymakers would select different values even if they had complete knowledge of the physical and societal impacts of gasoline use. The $2.00/gallon figure is simply one value out of a wide range of possibilities.

continued on next page

Box 9-C—The OTA Scenario for 2001: Max Technology Without Enforced Early Retirements—Continued

The 2001 penetration rates (beyond 1995 levels) of key fuel economy technologies will be:

● weight reduction	60 percent
● drag reduction	60 percent
● intake valve control	40 percent
● five-speed automatic	25 percent
● CVT	5 percent
● four-valve engine	40 percent

It appears that all body, engine, and transmission changes can be completed by 2005 without disrupting the normal lifecycle of these components. Consequently, by 2005 this scenario should start resembling the maximum technology scenario, because the economic assumptions of the regulatory push scenario would have matched the max technology scenario had lifecycle disruptions been allowed. In 2005, however, weight and drag reduction can reach 100 percent and 90 percent, respectively, versus the limit of 80 percent penetration of these technologies allowed in the max technology scenario because of insufficient industry design and retooling capacity. Further, addition of new technologies is more likely between 2001 and 2005, so that two-stroke engines and possibly other technologies may enter the fleet.

economy increase of 24.22 percent over 1995, or 36.55 mpg (including a 0.4-mpg test adjustment). The corresponding import fleet average would be about 38.4 mpg, for a 37.1-mpg overall fleet average assuming imports capture about one-third of U.S. sales volume.

The two-stroke engine is one of the most promising technologies for this timeframe, with some companies claiming such engines could enter the fleet by the mid-1990s. The primary benefit of the two-stroke would be more to allow high efficiency at relatively low cost than to greatly increase efficiency. However, advanced four-stroke engines with four-valves per cylinder and intake valve control will be almost as efficient as the two-stroke though at much higher cost. If the two-stroke is successful in demonstrating commercial reliability and satisfactory emissions control, it could add about another mile per gallon to the fleet average, primarily by its use in small cars that might not use intake valve control. To make a significant contribution by 2001, however, this engine would have to demonstrate its emissions capability within the next few years. Expecting a major contribution by 2005 might be more realistic.

Translating the scenario results into an effective fuel economy target demands consideration of both the structure of fuel economy regulations and the credits available to the automakers. The results represent the fuel economy obtainable by the fleet if all manufacturers use the full complement of technology derived by the analysis. However, each manufacturer would not attain the fleet fuel economy level specified by the scenario analysis—manufacturers building a range of cars smaller than the fleet average would tend to reach a higher-than-fleet-average fuel economy at this level of technology, and manufacturers with larger vehicles would attain a less-than-average fuel economy. Further, to the extent individual manufacturers build vehicles with higher or lower acceleration performance than the fleet average, their company fuel economies will tend to be lower or higher. Consequently, a standard similar in structure to the current uniform CAFE standard of 27.5 mpg and set at the fleet average mpg would not be achievable by several major automakers without radical changes in their size and performance mixes. They would have to sell a greater proportion of small or low-performance cars than they currently do.

If Congress wished to use a uniform CAFE target that would not force widespread violations, it would have to set the target a few mpg below the scenario results. As an alternative, it could allow credit trading between companies, so that a company exceeding the standard could sell its accumulated credits to another unable to meet the standard. However, it is not clear that credit trading would be effective with a standard set at the level defined by the scenario. This level considerably exceeds the level that would be chosen according to consumer values alone. In other words, unless credits have a very high monetary value, a company would likely choose a lower fuel economy level by retaining more consumer-desirable attributes (or by avoiding the most expensive fuel economy technologies, thereby obtaining the opportunity to sell its vehicles at a significantly lower price), rather than exceeding the standard and selling credits. Box 9-D briefly discusses the nature of this decision.

If regulations take the form of a size-class or interior-volume (VAFE) standard, Congress should be able to use the results directly in defining a target, since both the regulatory structure and the analytical method seek to give each automaker an equal technological challenge. In this case, a series of size-class standards or a single VAFE standard that would reach the target fuel economy can be constructed based on the projected size-class distribution of the fleet.

If regulations take the form of a uniform percentage increase over a baseline year, as in the Bryan proposal, Congress could likely set a standard fairly close to, though somewhat below, the percentage that would yield the scenario target and still make the standard achievable by most or

Box 9-D—CAFE Fines and the Availability of Mileage Credits

The fine for failure to comply with Federal fuel economy standards currently is $50 for each mile/gallon under the standard multiplied by the number of vehicles in an automaker's fleet. The proposed Senate Energy bill raises the fine to $200 for each mile/gallon by the year 1996. Although the principle of harmonic averaging of fuel economy values complicates the arithmetic, the size of the fine means *roughly* that, if a company is out of compliance, it should be willing to pay at least $200 per car to add a technology that would improve fuel economy by 1 mpg, assuming the technology does not adversely affect other vehicle attributes. If consumers value fuel economy and will pay more for a more efficient car, or if the technology affects other important vehicle attributes positively, the company might be willing to pay more than $200 for the technology; if the technology adversely affects performance or other vehicle attributes, the company might pay less.

What does this mean in real terms? A 5-percent fuel economy improvement is a large improvement, given today's advanced designs. For a 30 mpg car, 5 percent equals 1.5 mpg or $300 in avoided fines at the $200 rate, only $75 at the current rate.

The size of the avoided fine and likely low values for mileage credits (if credit trading is allowed) call into question the probability that significant credits will be available for trading. A company with the opportunity of accumulating credits also has the opportunity of using the fuel economy potential to instead boost the performance of its fleet. It is quite possible that the performance increase available by "trading off" 1.5 mpg—perhaps 1 or 2 seconds in 0-to-60-mph time—might be worth more to the company than $300 in mileage credits.

To gain another perspective on the decision, it is worth examining the value of fuel economy gains in terms of gasoline savings. The example cited above, a potential 1.5-mpg savings from a 30-mpg-base vehicle, represents a gasoline savings of about 19 gallons per year based on 12,000 miles of driving. Assuming gasoline prices in the $1.10-$1.50/gallon range, this is a very low savings. It implies that a company could justifiably add fuel economy technology well past the "consumer cost-effective" point if the potential payback from selling credits is $300. Put another way, the payback from selling credits justifies adding technology that would otherwise (without credits) require a high gasoline price, perhaps $3.00/gallon or more, for a cost-effective return.

all companies. The gap between an "attainable" standard and the scenario result is caused by differences in the level of technology among companies in the baseline year (see box 9-B) and changes in company size mixes that may have occurred in the intervening years. Credit trading may reduce this gap and allow a higher standard to be set, assuming marketable credits become available (box 9-D).

Congress may also wish to account for available CAFE credits in setting new standards. In particular, manufacturers may produce alternative-fuel vehicles and gain CAFE credits equivalent, for flexfuel vehicles, to half the gasoline theoretically saved if the vehicles are fueled exclusively with the alternative fuel, or to all the gasoline saved for vehicles dedicated to alternative fuels. The credits for flexfuel vehicles are capped at 1.2 mpg for 1995 and 0.9 mpg for 2001, so Congress could add these values to the scenario results to reach an attainable (adjusted) fuel economy. Congress should note, however, that adding the potential value of these credits to the estimated value of attainable fuel economy is contrary to the letter and spirit of the legislation establishing the credits: the legislation demands that the potential to earn credits *not* be used as an excuse to increase fuel economy standards. Such use would change the establishment of credits from a reward to manufacturers producing altfuel vehicles to essentially a requirement to produce those vehicles, since the standards would not be attainable without such production.

CONSUMER PREFERENCES

As shown, a significant shift in the new car fleet away from higher performance and larger vehicles and toward high fuel economy could yield very large increases in fleet fuel economy even without advances in technology.

Potential for large fuel economy gains through shifts in basic consumer-oriented attributes of the fleet poses a dilemma for policymakers. On one hand, if these changes can be accomplished by changing consumer preferences, the United States will achieve significant conservation benefits without likely long-term negative impacts on the industry—assuming domestic automakers maintain relative competitiveness.

On the other hand, if Congress tries to accomplish such changes *through regulation*, it risks reducing the attractiveness of new cars to consumers and possibly slowing vehicle turnover as consumers keep their old cars longer. Substantial difference between the fuel economy of new and old cars—1975 cars had fuel economies about half those of new cars—makes fleet turnover a powerful though diminishing force in increasing total fleet fuel economy. The danger of a standard high enough to require significant changes in consumer-oriented vehicle attributes is that it conceivably could *slow* net improvement of total fleet fuel economy. Further, making vehicles smaller does represent a potential safety problem, though one that can be mitigated by improvements in design and safety equipment (see discussion below).

Thus, if Congress wishes to set new fuel economy standards at levels likely to require large changes in vehicle performance and size characteristics, it must consider measures that would help shift consumer preferences toward high fuel economy. Obvious measures include gasoline taxes and vehicle purchase incentives ("gas sipper" rebates, "gas guzzler" taxes). This report does not evaluate the likely effectiveness and cost of such measures. However, given the relatively small difference between U.S. fleet fuel economy and those of the various European and Japanese fleets, with their much higher gasoline prices, and the limited sales success of domestic manufacturers in promoting smaller, more fuel-efficient models through favorable pricing and rebates, we believe shifting consumer preferences through economic measures will be difficult. The highest potential for success is likely to be sales shifts to higher-fuel-economy cars *within* market classes.

DEALING WITH NEW TECHNOLOGIES

Those analyses projecting fuel economy potential that have played a major role in the ongoing CAFE debate—analyses based either on the EEA model or on industry or industry-sponsored technology estimates—generally deal with relatively low-risk technologies that have already begun to penetrate the fleet (e.g., four-valve engines, roller cams, aerodynamic improvements, and so forth). By the year 2001 or 2002 (commonly chosen target years for the second stage of new fuel economy standards), technologies not now in the fleet, and thus *not included in analyses now being used to inform policy choices*, may play an important role in determining fleet fuel economy. This belief is bolstered by a simple examination, in retrospect, of what a list of "available technologies" (as defined in the EEA analysis) *would not have* included had it been compiled 10 or 15 years ago. In particular, the list would not have included four-valve-per-cylinder engines and electronically controlled transmissions, important components of fuel economy improvement today. It may not have included multipoint fuel injection either, a critical component of improved engines. An analysis based on existing technologies used to project fuel economy potential will likely miss key components of the actual fuel economy potential of the fleet of 10 to 15 years in the future. Further, since the EEA technology list excludes diesel technologies, a revival in market fortunes for this technology also could substantially alter the fleet's fuel economy potential.

To be evenhanded, we should note that the theoretical list could have included at least one technology—diesels—that plays almost no role in today's new car fleet. Although no technologies on the current list appear likely to be sidetracked by regulatory changes or performance problems, it is conceivable that some will not play a role, possibly because of style (advanced aerodynamics) or technical complexity (intake valve control). OTA believes the "upside" potential—the probability of additions to the list—outweighs the downside, or likelihood that current technologies will be dropped.

Potential new technology (and the possibility of a diesel revival) implies that *estimated* fuel economy potential for 2001 or beyond, when calculated using only available technology, may understate these values. For example, successful development of two-stroke engines could lead to their introduction into the fleet in the 1996 to 1997 timeframe. By 2001, if the first examples performed well, two-strokes could be used on several model lines. Developers of two-stroke engines claim fuel economy increases over current four-stroke engines as high as 30 percent;[10] this estimate appears optimistic. The more appropriate comparison is with advanced four-stroke engines with intake valve control that would likely be available in the same timeframe; this yields about a 3- to 4-percent improvement coupled with a substantial cost reduction. Similarly, drive-by-wire technology (i.e., the mechanical linkage of accelerator pedal and throttle is replaced by an electronic linkage with computer adjustment of throttle) could become widely available by 2001, especially for larger vehicles, yielding a speculative 2- or 3-percent "per vehicle" improvement in fuel economy. And improved turbo diesel engines, though not a new technology, could yield substantial benefits—up to 22 percent "per vehicle"—if they gained consumer acceptance now widely denied to diesels and could satisfy new emission standards.

What is the likely timing of these new technologies? Estimating the year any particular technology will be introduced into the fleet is difficult. Much of the information needed for the estimate is guarded by manufacturers and the decision to introduce depends on variable factors such as the company's competitive situation around the time of potential introduction, consumer preferences at that time, and so forth. However, certain technologies seem advanced enough to begin entering the market by or before 2001—weight reduction through extensive use of aluminum and Fiberglas-reinforced plastics in standard parts; major reductions in aerodynamic drag, with fleet average drag coefficients dropping well below 0.3; tires with reduced rolling resistance; and a variety of engine improvements, including use of five valves per cylinder, variable compression ratio engines, two-ring pistons, and use of lightweight ceramic or composite-material reciprocating parts. As noted, there are indications that two-stroke engines may be introduced by the middle 1990s, though compliance with tighter emission standards remains a significant roadblock for this technology.

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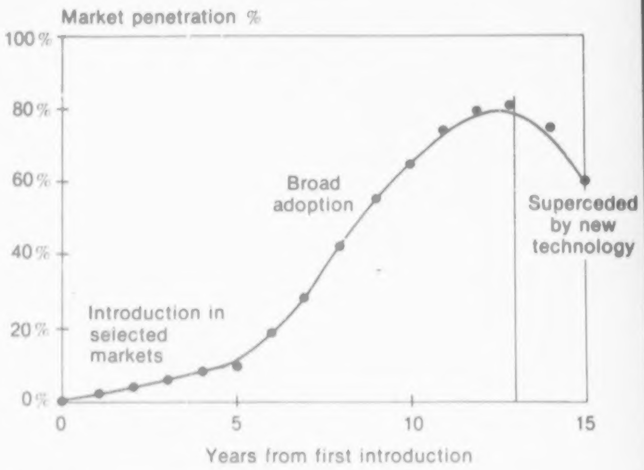
[10] The fuel economy increase is caused by a combination of improved engine efficiency, reduced engine and associated vehicle weight, and aerodynamic improvements made possible by the engine's greatly reduced size.

Technology introduction and *market penetration* are not synonymous. Prudent automakers introduce new technologies into specific market niches, perhaps a single model, and then gain experience with it over the next few years. Only when consumer reaction has been positive and no significant reliability or performance problems arise do automakers begin to move the technology broadly into their fleet. For domestic manufacturers, this will take an average of about 8 years, during which they will redesign virtually their entire product line. For the Japanese, the redesign period is shorter, perhaps as short as 4 years for some companies. However, an incentive such as a new fuel economy standard clearly could accelerate this process. Figure 9-2 illustrates a market penetration profile typical of recent experience for a domestic manufacturer. Although widespread introduction of the technology would, of course, lag behind the curve of the company introducing the technology, other automakers would likely take less time in proving out the technology in their fleets because they would have access to the experience of the first company. In other words, a curve for the fleet as a whole would begin to overtake the curve for the introducing company.

The implication of this profile is that technologies introduced by 1995 or so will achieve only modest market penetrations by 2001, but can achieve high levels of penetration within only a few years later.

Figure 9-2—Typical Market Penetration Profile of New Technology



SOURCE Energy & Environmental Analysis, Inc., 1991

Congress is faced with an important dilemma in crafting fuel economy standards for the longer timeframe: how to encourage development of new technologies while accounting for inherent uncertainty in their future potential? This dilemma may be eased by incorporating administrative discretion in future standards enforcement—i.e., by setting standards that assume a significant degree of success in technology development, but including an escape clause that permits enforcing agencies to lower standards if such success does not materialize. This strategy will work only if individual companies vigorously compete for technological dominance, and if they know that the technological success of one company will rule out an administrative delay in the standards.[11] Further, Congress must be able to trust the administrative agency—presumably, the Department of Transportation—to grant delays only in the face of incontrovertible evidence that standards are not achievable.

A final note to this part of our discussion:

The relative *short-term* inflexibility of automaker manufacturing strategies due to their need to make orders for outsourced components and manufacturing dies and other equipment years in advance of the model year, coupled with the substantial risk involved in prematurely moving new technologies into the fleet, presents Congress with a significant dilemma in specifying fuel economy standards for the relatively near future (e.g., 1996–98). If Congress does not specify stringent standards for this timeframe, it risks a fait accompli of noncompliance by manufacturers later on with little remedy other than massive, and perhaps politically unacceptable, economic penalties. On the other hand, demanding short-term, fleetwide fuel economy increases may expose some automakers to large risks associated with moving new technologies widely into their fleets without testing the technologies for a few years in one or two models. A potential solution to this dilemma is to designate interim milestones for automakers to demonstrate a few high-fuel-economy models with requirements for minimum production runs. In other words, have automakers show they're testing new designs and technologies in a real-world situation, but don't require them to risk their whole fleet.

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[11] It should be noted that GM and Ford successfully won a rollback in the 27.5-mpg standard even though Chrysler fought the rollback and planned on meeting the standard.

ECONOMIC PRESSURE ON THE INDUSTRY

New fuel economy standards pose both risks and potential economic benefits to automakers. Risks arise from the capital expenditures necessitated by the standards, possible negative reaction to vehicles meeting the standards and consequently slower purchase rates, and the potential for vehicle reliability problems and other difficulties if the standards force technological change at a rate faster than companies can comfortably accommodate.

The risks associated with increased capital spending and negative consumer reaction appear virtually inevitable unless one assumes that either an oil crisis of some sort will occur or the Federal Government will take important steps to align consumer preferences with the direction that stringent fuel economy standards will take the industry. Such a government effort—which could include a large increase in gasoline taxes, or tax breaks or rebates for buying vehicles with higher fuel economy—could serve well as market adjunct to fuel economy regulation.

Potential benefits to automakers stem from the unstable nature of the world oil market and the difficulty individual manufacturers have in adapting their vehicles in response. If another oil crisis were to send gasoline prices skyrocketing or limit fuel availability, ultra-high-efficiency vehicles clearly would become extremely attractive. Ironically, companies that unilaterally set out to produce such vehicles might, in the short term, have a difficult time competing with companies that focused instead on performance and other vehicle attributes that conflict with high fuel economy but nevertheless are attractive to today's vehicle purchasers. In other words, individual companies may find preparing themselves to deal with a possible energy crisis difficult unless they know other companies were doing the same. A fuel economy standard that requires each automaker to take similar steps to improve fuel economy could provide the type of pressure that would allow this preparation without the competitive risk such preparation would otherwise cost.

The risks of reliability and other problems associated with technology introduction can be reduced or eliminated by sufficient lead times for the standards, allowing companies to pace through the steps necessary to minimize problems with new technologies and designs. Lead times are also critical to allow industry to recover investment on existing models. The costs and risks of any policy that forces the auto industry toward very rapid redesign of all existing models—a so-called "maximum technology" standard—can be understood in the context of industry cost structure, product lifecycles, and product lead-time requirements.

The auto industry has large fixed costs that it incurs in developing and tooling up for a new model. Currently, many high-sales-volume models require spending $1 billion prior to the first car being rolled out of production. The automaker hopes to pay off this investment over the life of the model, which typically has averaged about 8 years (longer for light trucks). Thus, a large part of the "cost" of a new car is amortization of the initial investment. The automaker must guess the sales volume over the 8-year model life to calculate the required per-car payback of this investment. If the car is more successful than the automaker hoped for, the model line will be very profitable, but if it is less successful, the line will lose money. An automaker with several models will usually have winners and losers; on average, he hopes to realize an adequate return on total investment.

The $1 billion initial cost for a new model is spent over the 5-year period when the model is conceived, developed into a prototype, tested, and certified to all applicable safety and emissions standards, and while the manufacturing plant is retooled to build the new model. The 5-year lead time means that new models for 1996 are now in the detailed planning stage. The 1996 models need to remain in production until about 2004 if the automaker is to obtain the expected return on investment. For engines and transmissions, the lifecycle may be longer—some current engines date back to the early 1970s, although they have received evolutionary updates.

A maximum technology scenario requires that automakers redesign all of their products applying all available technologies on or before the target year. It is obvious that such a requirement will be meaningless for 1996, because lead time is insufficient to redesign all products much less produce them.

If the target year is 2001 or 2002, it is possible *in principle* to redesign all products to include maximum technology. However, this will lead to two significant burdens on automakers. First, models that will be introduced in 1994/1995 and cannot be withdrawn at this late stage will have to be phased out a few years before the end of their normal lifecycle. If a model loses 2 or 3 years of life, return on investment to the maker will be significantly reduced.

Second, instead of the U.S. industry experience of 13 years, automakers would have only 9 or 10 years to redesign all of their products, including models that have just been redesigned. This can be done if automakers accelerate the process by hiring more engineers (though there is a limited pool of experienced engineers), increase overtime, or make the design process more efficient. However, shortened lead times could result in designs that are not fully tested and would be at increased risk of market failure. The risk is less for Japanese automakers, some of whom have reduced lead time to 4 years[12] and reduced initial costs to the point that their product lifecycle can be 4 years. U.S. automakers have not been able to duplicate this.

The burden associated with an early target year for a standard based on maximum technology requirements may be aggravated by recent Clean Air Act revisions and new safety requirements, which have imposed additional design burdens on all automakers.

Selection of an appropriate target date for a maximum technology scenario involves a tradeoff of the risks and costs associated with accelerated design schedules and shorter product lifetimes and the benefits of moving the fleet more rapidly toward higher fuel economy. Given the U.S. cycle of 8-year model life and 5-year lead time, and the proximity of the 1992 model year, the 2005 model year might seem a good target date for policymakers who are somewhat risk-averse.[13] A model year 2005 target would reduce risks to U.S. automakers and avoid the costs of prematurely introducing technology across all models on an accelerated schedule. On the other hand, U.S. automakers have successfully accelerated product schedules in the past, for example during the middle 1970s and early 1980s, and could do so again, though at high costs (and perhaps at higher risk than previously, because those accelerations were due primarily to market pressures). Also, some potential exists that U.S. automakers can achieve the shorter turnaround schedules of some Japanese makers. Depending on the value they place on the benefits of accelerating fuel economy improvements, some policymakers might prefer an earlier target date for a maximum technology scenario.

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[12] Probably longer for light trucks.

[13] In other words, automakers have already begun design process for 1996 or 1997 models, and these models will not undergo a major changeover until 2004 or 2005.

POTENTIAL EFFECT OF HIGHER FUEL ECONOMY STANDARDS ON VEHICLE SAFETY

Industry and Administration opposition to new fuel economy standards has included arguments that higher standards, such as proposed by S.279, would force consumers into a new fleet of smaller cars significantly less safe than a new fleet with an unchanged size mix—and perhaps even less safe than the current fleet.[14] In OTA's view, unless sharp fuel economy improvements are demanded over a period too short to allow vehicle redesign, or the fuel economy requirements are so stringent they can be met only with drastic downsizing, it is unlikely that *absolute* levels of safety would decrease. Continued introduction of safety improvements and wider use of already-introduced improvements should compensate for adverse effects of moderate downsizing. Further, if given enough time, automakers can significantly improve fleet fuel economy *without* downsizing (though with some weight reduction), and without any likely safety impact. Nonetheless, there *is* cause for concern about the relationship between fuel economy and safety, and there is a reasonable probability that further downsizing—especially a reduction in exterior dimensions—would cause the fleet to be less safe than it would otherwise be. However, we also find the debate about the relationship between fuel economy and safety has at times become overheated,[15] and assertions on both sides of the debate seeking to demonstrate the magnitude of risk are frequently flawed or misleading.

Much concern about safety and vehicle size stems from the physics of car crashes and an examination of traffic safety records over the past few decades. Although there are very safe small cars and relatively unsafe large ones, in comparing two similar-design cars of different size, the smaller, lighter car will be inherently less safe, especially in vehicle-to-vehicle collisions. Given similar materials and design, a passenger in the smaller, lighter car will experience greater deceleration forces in such a collision than a passenger in the larger, heavier car. Further, the management of deceleration forces is inherently easier in a large car as there is likely to be greater "crush space"—the volume of deformable structure available to absorb the forces generated by an accident. Also, cars made narrower and shorter without compensating for changes in center of gravity and suspension design—the center of gravity is not easy to change for sedans where passengers sit upright and adequate headroom must be maintained—are more prone to rollover, an accident type that exposes vehicle occupants to a high risk of serious injury and death, particularly if seat belts are not used.

Actual safety records generally bear out this analysis. For example, the Insurance Institute for Highway Safety reports death rates associated with several GM cars that have been downsized since 1977 rose an average of 23 percent. Some safety analysts have questioned the validity of the comparison between old and new versions of the same models, particularly because the Institute did not correct for differences in miles driven.[16] However, the Institute has shown that there have been little or no differences in death rates between old and new versions of the same model that had *not* undergone downsizing—implying that downsizing did have a negative impact on occupants of the affected cars. Of course, it may be possible that accompanying weight reductions made the downsized models less dangerous to other cars on the road, but this type of effect could not be accounted for in the data.

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[14] For example, see J.R. Curry, Administrator, National Highway Traffic Safety Administration, statement before the Subcommittee on Energy and Power, House Committee on Energy and Commerce, Oct. 1, 1990.

[15] The rhetoric has ranged from asserting that safety and vehicle size are essentially unrelated to suggesting that S.279 be referred to as "The Highway Fatality Act."

[16] Aside from driving more, occupants of new cars are more likely to use seat belts than are occupants of older cars. The two factors work in opposing directions in affecting fatality rates.

Also, according to the National Highway Traffic Safety Administration (NHTSA), accident statistics show that smaller cars are more prone to rollover[17] and experience far more rollover fatalities than large cars. NHTSA's recent study of car size and its relationship to fatality and injury risk in single-vehicle crashes found a significant increase in occupant fatalities and moderate-to-serious injuries caused by the general size reduction of the fleet, with up to a 50-percent increase in rollover propensity accounting for the increased fatalities.[18] The data presented in this study appear to pin more blame for the increase in rollovers on the shift from full-size cars to compacts and subcompacts, and to imports, than to downsizing *within* vehicle classes,[19] though the data do show some of the downsizing effects observed by the Insurance Institute.

NHTSA's analyses indicate that small cars are less safe in situations other than rollover. They have calculated that the fleet size reduction is associated with about a 10-percent increase in fatalities and a 15-percent increase in serious injuries in single-vehicle nonrollover crashes, and that a collision between two small cars has about a 10-percent greater likelihood of resulting in serious injuries than a similar collision between two cars that are 1,000 pounds heavier[20] (as discussed later, we believe the differential safety risk is more likely due to size rather than weight differences between the two sets of vehicles). Also, NHTSA concludes that its crash-test data from the New Car Assessment Program indicate that in crashes into a barrier, "small, light vehicles expose the occupants to more danger than large, heavy cars...because crash forces are imposed on the small car occupants quickly and in a concentrated manner, while occupants of large cars experience a more gradual deceleration."[21] (Again, we believe the difference to be due primarily to size.)

NHTSA concluded that the changes in the size composition of the new car fleet between model years 1970 and 1982, which resulted in a shrinkage in median curb weight of new cars involved in fatal collisions by about 1,000 pounds, a wheelbase reduction of about 10 inches, and a track width reduction of 2 to 3 inches, "resulted in increases of nearly 2,000 fatalities and 20,000 serious injuries per year"[22] over the number that would have occurred had no downsizing occurred.

To date, the above evidence may have played a less prominent role in communicating the perceived dangers of vehicle downsizing to Congress—and certainly has played a less prominent role in communicating these perceived dangers to the public—than other, less relevant evidence about crash test results between larger and smaller cars and overall fatality rates of cars of greatly differing size and weight. In reality, the comparatively greater safety of a larger, heavier car demonstrated by this evidence is a two-edged sword, since the higher weight of that car also represents more of a danger to other cars. Conversely, while smaller, lighter cars may offer less protection to their occupants, their lower weight reduces risks to other cars. In particular, weight per se may not add to the *overall* safety of the fleet, because the advantage of greater weight to a heavy vehicle, that it reduces relative crash forces, is counterbalanced by the greater crash forces it *transmits* to any car it collides with.[23] To state it another way, although an individual might wish to choose a heavy car to enhance his or her personal safety, society does not necessarily gain from this choice because the heavier car represents an added threat to other cars on the road.

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[17] C.J. Kahane, "Effect of Car Size on the Frequency and Severity of Rollover Crashes," National Highway Traffic Safety Administration, May 1990.

[18] U.S. Department of Transportation, National Highway Traffic Safety Administration, *Effect of Car Size on Fatality and Injury Risk in Single-Vehicle Crashes*, August 1990.

[19] Ibid., p. 33, figures 1 and 2.

[20] U.S. Department of Transportation, National Highway Traffic and Safety Administration, "Effect of Car Size on Fatality and Injury Risk," 1991, unpublished paper widely distributed to Congressional Committees, hereafter referred to as NHTSA Car Size Summary.

[21] Ibid.

[22] Ibid.

The broadening of the debate to focus on societal risk—the question of whether or not society as a whole benefits or loses from a shift to smaller, lighter cars—is the needed focus for policymakers trying to decide whether to set new fuel economy standards at levels that might require such a shift. From this focus, evidence about factors such as increased rollover danger, single vehicle collision results, and the like are of dominant importance. Data concerning collisions between cars of greatly different size and weight are important to individual consumer decisions and, hence, are relevant and often stressed in policy arguments,[24] but are of lesser or even little importance to the broader issues of societal risk of fleet downsizing. In a fleetwide downsizing, large cars would get smaller and lighter also, and would be less dangerous to small cars; the weight differences among cars would not necessarily become greater.

Nevertheless, available data and analysis on single-vehicle crashes, on "before and after" fatality rates for downsized cars, and on differential injury and fatality rates between crashes of two small cars versus crashes of two large ones (as noted, occupants in the crash of two large cars generally fare better than those in two small cars[25]) strongly imply that, to the extent that any CAFE legislation leads to significant downsizing of the fleet (a shift to smaller size classes or designs that maintain interior volume but reduce exterior dimensions), safety will be reduced, all other things remaining equal.

This last statement is worded very carefully, with good reason. First of all, policymakers weighing new fuel economy legislation should recognize that improved fuel economy and downsizing are not synonymous, and the extent of any fuel economy/safety tradeoff depends on how much downsizing would be required. According to OTA's analysis, even a year-2001 standard of 40 mpg, as proposed by S.279, could be met without significantly reducing average vehicle dimensions (both interior volume and exterior size)—though not without cost.[26] Although average vehicle *weight* would be reduced, it is not clear at all this will reduce overall fleet safety. By 2001, the new car fleet could achieve about 38 mpg using existing technology coupled with a reduction in performance and size to 1987 levels (the size reduction is small), and probably gain sufficient credits for the remaining 2 mpg by selling large numbers of flexfuel and dedicated alternative-fuel vehicles. On the other hand, S.279's 34 mpg/1996 standard probably is unattainable without a significant shift in sales to smaller vehicles.

Second, even if new cars *are* forced to be smaller than today's, the condition of "all other things remaining equal" is not likely to apply. A long history of analysis of accident statistics, crash testing, and research into safety systems and prototype safety vehicles demonstrates that vehicle design is extremely important in vehicle crashworthiness and crash avoidance. A great deal of safety equipment has already been added to today's vehicles, and their basic structural designs reflect considerable experience with crash analysis. Considerable "headroom" for further safety improvements still exists, however. In fact, data demonstrate that redesign efforts aimed simply at improving the least safe cars in the current fleet to the level of the most safe could have substantial positive impact on overall fleet safety.

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[23] As discussed elsewhere, some studies do tie vehicle weight to overall fleet safety, but most of these studies use weight as a general measure of size, and don't try to separate out the effects of weight and other size measurements. We believe that variables such as wheelbase and track width, which are strongly "colinear" with weight (i.e., they are closely related to weight, getting larger or smaller as weight gets larger or smaller, so it is hard to separate out their effects from the effects of weight), are more important to overall fleet safety.

[24] For example, NHTSA has widely distributed a videotape of two crash tests between cars of dissimilar size that show the small cars being devastated by the crashes. The videotape states that the crash results demonstrate the danger inherent in new fuel economy standards and vehicle downsizing. However, the videotape shows only that cars are at a serious disadvantage if struck by another vehicle of much larger weight. Unless fleetwide downsizing induced by new fuel economy standards were to lead to a large increase in collisions between vehicles of greatly dissimilar weight, the dramatic crash damage shown in the videotape has little relevance to the societal danger—measured in injuries and fatalities per year—posed by the new standards. It is not at all clear that downsizing would have this effect, except possibly during a transition period. In fact, NHTSA has identified *other* types of crashes—particularly single-vehicle rollover crashes—as the most likely source of increased fatalities from further downsizing.

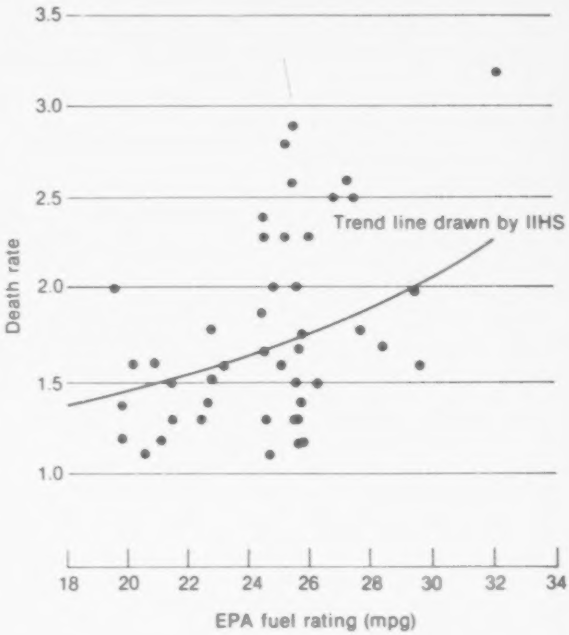
[25] NHTSA Car Size Summary.

[26] Achieving such a high fuel economy target in this timeframe would require a rollback in vehicle performance to 1987 levels, early retirement of several model lines, and the use of some technologies that could not recoup their costs through fuel savings unless gasoline were $2.00/gallon.

An examination of different models of the same size or fuel economy shows large differences in death rates. As shown by the plot in figure 9-3, which is used by the IIHS to illustrate that better fuel economy can be detrimental to safety, a consumer can pick many cars in the 25- to 26-mpg range that are safer than many in the 20- to 21-mpg range. In fact, although the trend line in figure 9-3, as drawn, implies a direct correspondence between vehicle fuel economy (and size) and safety, the data are so scattered that a substantially different line could be drawn by dropping a few outlying points. The data more clearly illustrate the importance of factors *other than fuel economy and size* in determining vehicle safety.[27]

It seems clear that, were significant downsizing of the fleet to occur, a good portion, and perhaps all, of any resulting loss in safety could be balanced by improvements in safety design. However, to the extent the improved designs would work equally well with larger vehicles and provide still greater safety to them, there will have been some safety opportunity *forgone*—i.e., if the improvements were made *without* downsizing, the safety of the fleet would be better still.

Figure 9-3—Relationship Between Deaths Per 10,000 Registered Cars and Fuel Economy, 1985-87 Four-Door Models



SOURCE: Insurance Institute for Highway Safety, 1990

Even when safety improvements work equally well on small and large cars, improving the relative safety of all cars will shrink the *absolute* safety gap between large and small cars (measured in deaths per 100 million miles traveled or per million vehicles). But not all safety improvements work equally well on all car sizes. Safety improvements that focus particularly on problems that afflict small cars more—e.g., rollover—would tend to shrink the absolute *and relative* safety gaps between large and small cars. As an example: wider use of anti-lock brakes will provide greater directional stability in emergency braking. Since loss of directional control is often a precursor to rollover, wider use may also provide a greater absolute benefit to lighter cars. Further, current safety performance standards—as opposed to requirements for specific equipment additions—demand the same performance (e.g., passenger survival in a 30-mph frontal crash) from all cars regardless of size. Compliance with these standards should further shrink the safety gap. *To the extent that such differential improvements occur, shifting to a smaller fleet will be less damaging to safety than a simple extrapolation from past trends would project.*

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[27] A statistical analysis of the IIHS model demonstrates that the significance of the fuel economy/safety relationship described in the model is low; that the shape of the curve is dominated by a few outlying data points—inexcusable in an analysis that attempts to distinguish immutable truths in a field where simple design flaws can cause high death and injury rates well out of proportion to what otherwise could be expected from vehicle size characteristics; and that the model ignores variables clearly shown to play a major role in traffic fatality rates. J.D. Khazzoom, supplemental material to testimony before the Consumer Subcommittee, U.S. Senate Committee on Commerce, Science, and Transportation, Apr. 10, 1991.

As a corollary to this point, in the past, identification and examination of safety problems often yielded relatively simple solutions that could be applied to the next generation of car designs, or even retrofitted to current model lines. Acceptance of the statistical results of studies examining past behavior of vehicles does not imply that this behavior is unchangeable. The letter accompanying the NHTSA study states, "The increase in rollover rates could be expected because of the physical characteristics of smaller cars. It's a simple law of physics. The reduced weight and shorter wheelbase leaves smaller cars more difficult to keep on the road in emergency maneuvers. And once off the road, they are more likely to roll over, which in turn increases the risk of fatal injury."[28] This is not sound physics. There is certainly no immutable law of physics that makes small, light cars inherently more difficult than large, heavy cars to keep on the road in emergency maneuvers.[29] Although we are not aware of any studies that compare the handling characteristics of cars in different size and weight classes, many cars rated highly in emergency maneuvering by test organizations such as Consumer Reports are small, light sedans. And to the extent that added rollover risk in small cars is associated with their narrower wheel track, during 1970-1982 the median track width of the U.S. auto fleet narrowed by only two to three inches;[30] reversing this shift should reduce rollover rate but not create an impossible tradeoff with fuel economy.[31] We expect that identification of vehicle rollover as a serious problem in smaller cars (and likely future NHTSA rulemaking on rollover) will lead to compensatory measures—improved suspensions, possibly some increase in track width, measures to reduce passenger ejection—that will alleviate the rollover risk difference between small and large cars measured by NHTSA.

We note that NHTSA has rated rollover as its number one vehicle safety issue and has done extensive analysis of the rollover phenomenon, but claims it has been unable, as yet, to define a clear "fix" for the problem[32] . . . implying that OTA's confidence in a timely solution may be misplaced. In its summary report, NHTSA bolsters this position by stating that its analysis methods do not identify which individual vehicle size parameter (track width, curb weight, wheelbase, etc.) is the principal "cause" of the added rollover proneness of small cars. We agree, in general, that it is difficult to draw precise conclusions from statistical analyses when several variables are related to each other, as is the case here. However, analysis results appear to point quite strongly to track width as the primary characteristic affecting rollover,[33] and thus suggest widening track width as having clear potential to reduce rollover risk.

It is clear that the mechanisms of problem identification and solution and continual design changes have been at work in the recent past. During the period CAFE standards have been in effect, when the weight of the average automobile dropped by about 1,000 pounds and exterior dimensions shrank as well, and when the supposed adverse safety impacts were felt, the safety record of the U.S. fleet improved substantially—between 1975 and 1989, death rates for passenger cars declined from 2.43 per 10,000 registered cars (2.5 per 100 million miles) to 1.75 per 10,000 registered cars (1.7 per 100 million miles).[34] In other words, *at worst* the fleet changes somewhat reduced the fleet's overall improvement in safety during this period. Not surprisingly, this outcome is interpreted in radically different ways: by proponents of more stringent standards, as indicating that better fuel economy was achieved without compromising safety, in fact with substantially improved safety; by opponents, as indicating that nearly 2,000 lives per year that *could have been saved* were not, because of forced downsizing of the fleet.[35]

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[28] U.S. Department of Transportation, National Highway Traffic Safety Administration, "Vehicle Downsizing Hurts Auto Safety, Skinner Says," press release of Sept. 14, 1990, quoting NHTSA Administrator J.R. Curry.

[29] Large, heavy cars may have more directional stability than small, light cars, but tend to be less nimble. The relative tradeoff between the two in the wide range of situations where vehicles are at risk of leaving the road is unclear. Further, improved tires and more widespread use of anti-lock brakes, which will improve directional stability during braking for *all* cars, may lessen small cars' disadvantage in directional stability.

[30] NHTSA Car Size Summary.

[31] The tradeoff exists because widening a car's wheel track will somewhat increase its aerodynamic drag and weight, reducing its fuel economy.

[32] D.C. Bischoff, Associate Administrator for Plans and Policy, NHTSA, letter to S.E. Plotkin, OTA, June 14, 1991.

[33] C.J. Kahane, U.S. Department of Transportation, National Highway Traffic Safety Administration, *An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars-Federal Motor Vehicle Safety Standards 206 and 216*, DOT HS 807 489, November 1989.

Similarly, this past record is being used to predict and interpret, from different viewpoints, the likely outcome of *future* standards: in support (of new fuel economy standards), that increases to CAFE standards, even if accompanied by significant downsizing, would not necessarily be accompanied by a net reduction in vehicle safety and thus do not represent a compromise of safety; and in opposition, that some portion of expected improvements in safety will be nullified (and possibly, that overall safety will actually decline, though we consider this doubtful except in extreme circumstances) by further downsizing if new standards are legislated. Both viewpoints are, at least in part, correct. The first focuses on multiple goals (better fuel economy and improved safety) and implicitly accepts the possibility of balancing one against the other; the other focuses on safety as the primary goal, not to be traded off against fuel economy.

Third, to our knowledge, no statistical analysis has examined the effect of overall weight and size *distribution* on safety. Yet in multiple car accidents, a major factor in overall fleet safety appears to be wide differences in weight among vehicles on the road, with collisions between vehicles of grossly unequal weight resulting in extreme danger to the occupants of the lighter (and generally smaller) vehicle. If the entire fleet were to be reduced in weight, the weight *distribution* of the fleet need not become wider, and it might become narrower—except, perhaps, during a transition phase when old (heavy, large) cars and new (light, small) cars share the road. In fact, general weight reduction of the fleet over the past decade and a half has been characterized by a tendency for the fleet to become more uniform in weight, with fewer vehicles at the extremes—during 1978 to 1987, for example, cars in the 2,500 to 3,000-pound weight category, in the middle of the market, soared in market share from 19.6 percent to 58.7 percent.[36] We note, however, that the continued presence of trucks sharing the roadway with autos, and the greater popularity of light trucks, will act against this effect.

Fourth, the magnitude of the effect on injuries and fatalities estimated by NHTSA for 1970 to 1982 cars may be a poor predictor of—and, we believe, would likely overstate—the potential effect of future downsizing of similar magnitude, *even if, contrary to our expectations, the extended use of airbags and other safety technologies fails to narrow the safety gap between large and small vehicles*. This is because, except for rollover accidents, the NHTSA analysis lumps together data from the earliest years of downsizing and shifts in size mix—when safety implications of downsizing may not have been fully understood by vehicle designers and when designs of some small import cars had not yet incorporated modern concepts of crash protection—with data from later years when vehicle designs began to incorporate improved understanding of crash protection (gained in large part through NHTSA testing). We are not aware of NHTSA analyses examining *trends* in the effect of downsizing on fatality and injury rates (again, except for rollover accidents), but we hypothesize that the magnitude of the effect likely became smaller over the 1970-82 period. In other words, we expect redesign and downsizing of an older model or a shift downward across size classes during the end of the time period would have had substantially less impact on fatality and accident rates than a similar shift at the beginning.

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[34] National Highway Traffic Safety Administration, *Fatal Accident Reporting System 1989*, draft, table 1-2B. For *all* motor vehicles, death rates declined from 3.23 per 10,000 vehicles (3.4 per 100 million miles) to 2.38 per 10,000 vehicles (2.2 per 100 million vehicles), table 1-1.

[35] NHTSA Car Size Summary.

[36] From data in R.M. Heavenrich, et al., "Light Duty Automotive Fuel Economy and Technology Trends Through 1987," U.S. Environmental Protection Agency, 1987, compiled and analyzed by J.D. Khazzoom.

As an interesting footnote to this point, NHTSA has examined changes over time and across weight classes of its crash-test results,[37] but has not evaluated how differences among weight classes have changed with time. This type of analysis would be necessary to detect unequal improvement of crash safety across weight classes, the effect we suspect should have happened during the 1970 to 1982 model years, and perhaps later as well. However, the paper describing the NHTSA analysis does comment that, "from closer examination of the individual data . . . many of the poorer performing small cars were tested in the early years of the NCAP (Federal crash testing program) and . . . attrition is gradually eliminating these vehicles."[38] In other words, for the smaller cars, the combined data for all years during which downsizing occurred does not reflect rapid learning and vehicle improvement during the overall time period.

Fifth, the point of view that focuses on safety *forgone* implicitly assumes future safety measures will be taken essentially independent of circumstance—i.e., whether or not further downsizing were to occur. Thus, if the fleet downsizes, it loses safety from the downsizing but gains from other measures ranging from the implementation of side-impact standards to increased sales of anti-lock brakes. If the fleet does not downsize, it will gain the safety benefits of maintaining its current size mix *and* retain all the safety benefits that would have accrued with downsizing. This ignores the reality that consumers respond to their perceptions of highway safety and adjust buying habits accordingly, automakers similarly adjust designs to consumer demands, and governments adjust regulatory behavior to perceived public dangers as well as voter concerns. In other words, if new fuel economy standards lead to downsizing and the *potential* for a reduction in safety, future consumer, government, and automaker behavior will likely act to compensate.

We note that NHTSA's rating of rollover as their primary focus of regulatory attention is an excellent example of a response to the effects of a shifting market, in this case, increasing sales of light trucks and small cars. If this focus leads to rulemaking that improves auto safety, it will be disingenuous to claim that the fleet *could have been safer* had the market never shifted in a way that led to the rulemaking in the first place.

Another example of this process is occurring today, this time based on public reaction. Although in the recent past many Americans did not rate safety very high as an attribute they demanded in a new car, this attitude clearly has begun to change. Consumer surveys report new interest in safety[39] and automakers have responded with increased advertising emphasis on safety features and plans to add more. Automakers clearly are adjusting their plans to move airbags and anti-lock braking systems into lower-price models as inclusion of these systems provides a major marketing advantage. It seems reasonable to project that any new safety concerns associated with new fuel economy standards will accentuate this process.

We have a number of additional comments about the safety/size issue. First, although weight may be a factor in determining relative deceleration forces on passengers in vehicle-to-vehicle crashes, weight reduction by substituting lighter-weight but equally strong materials need not affect safety in other crashes (single-vehicle collisions), and may conceivably yield a net safety gain if substitute materials have strength and flexibility characteristics superior to original materials.[40] In other words, it may not be correct to assume that weight reduction *per se* will compromise safety. In fact, in its testimony to Congress, IIHS has carefully refrained from identifying weight as the vehicle characteristic of primary significance to safety, instead focusing on exterior dimensions—length and width. Given the importance of adequate crush space and the role of vehicle track width in rollover propensity, this makes sense.

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[37] J.R. Hackney, W.T. Hollowell, and D.S. Cohen, "Analysis of Frontal Crash Safety Performance of Passenger Cars, Light Trucks and Vans and an Outline of Future Research Requirements," National Highway Traffic Safety Administration, International Technical Conference on Experimental Safety Vehicles, 1989.

[38] Ibid., p. 6.

[39] For example, an Insurance Institute for Highway Safety survey of new car dealers in the Washington, DC area found that dealers report quality and safety as the top considerations of their customers, and a national survey conducted by the Roper Organization in June 1990 for the Insurance Research Council found that occupant protection has emerged as a leading factor in deciding which car to buy. B. O'Neill, President, IIHS, personal communication, June 10, 1991.

A number of studies have tied average vehicle weight to overall fleet safety. However, vehicle weight is closely correlated with vehicle size variables such as wheelbase and track width, so it is difficult to separate out individual effects of size and weight on fleet safety. Unfortunately, many of the statistical studies identifying weight as a critical fleet safety factor do not consider size variables,[41] and thus cannot conclude that weight is the key factor in the fleet safety equation.

Second, although we are basically optimistic that changes in design can compensate for considerable downsizing, we must also note that some safety equipment adds weight to vehicles or takes up interior space; and those setting CAFE standards must recognize that future government requirements for equipment such as anti-lock brakes, side-impact protection, padding to reduce head injuries, and air-bags will somewhat reduce the potential for efficiency improvements. However, some of the immediate negative impacts of new standards, such as increased weight, may be reduced or eliminated over time as manufacturers innovate or adopt superior designs of competitors. An interesting case-in-point: manufacturers fought bumper standards designed to guard against property damage in low-speed collisions, primarily on the grounds of added weight and expense, and eventually managed to get standards rolled back. Recent tests of numerous vehicles in low-speed collisions show that the vehicle offering the best protection, the Honda Accord, also has one of the lightest bumpers[42]—the Accord's bumper design achieves maximum protection with minimum weight gain. If Honda's competitors adopted its bumper design, the fleet could achieve significantly more damageability protection at minimal weight increase, and in some cases, at a weight reduction.

Third, although traffic accidents kill about 45,000 Americans, injure an additional 4 million, and cost society about $70 billion (in 1986 dollars) each year, research to improve automobile safety is funded at a low level in comparison to other life-threatening problems. As discussed in a recent Transportation Research Board report,[43] Federal funding for safety research has been cut by 40 percent since 1981 despite growing problems of an older driving population, use of larger trucks, and an increasingly inadequate highway system. Currently, annual Federal funding is only about $35 million. Given the recent history of the Federal safety research effort and reports that significant opportunities still exist for improving vehicle safety,[44] any arguments that more stringent fuel economy standards will lead to vehicle downsizing and more crash-related deaths and injuries should be reexamined in the light of the existing potential to counteract some of this negative impact with continued improvements, facilitated with added research funding, in vehicle crash avoidance capabilities, occupant protection, highway safety design and operation, and other safety factors.

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[40] Also, as noted, weight's *protectiveness* for passengers of the heavier vehicle in a crash translates into added danger to passengers of the other vehicle. The net effect of weight on overall safety may be neutral.

[41] A key analysis by Crandall and Graham (R.W. Crandall, and J.D. Graham, "The Effect of Fuel Economy Standards on Automobile Safety," *Journal of Law and Economics*, April 1989), does not examine the size variables. Also, according to an analysis of the Crandall-Graham models by J.D. Khazzoom (who is currently expanding this work under contract to the Congressional Research Service), the models use average weight only and take no account of the distribution of weight changes in the fleet. In fact, most analysts believe that narrowing the weight distribution of the fleet (i.e., reducing weight differences among the various models) will improve fleet safety, and previous changes in average weight were accompanied by large changes in weight distribution.

[42] Insurance Institute for Highway Safety, *Status Report; Special Issue: Annual Low-Speed Crash Tests*, vol. 26 No. 2, Feb. 16, 1991.

[43] Transportation Research Board, *Safety Research for a Changing Highway Environment*, Special Report 229, Washington, DC.

[44] Ibid.

Fourth, some of the oft-used arguments about the relationship of CAFE, fuel economy, and vehicle safety are internally inconsistent. Many organizations and individuals claiming that CAFE standards have been ineffective in gaining large fuel economy benefits (i.e., most increases in fuel economy, thus, most physical changes in the fleet, are said to have been associated with rising oil prices not regulations) also have been claiming that CAFE standards have adverse safety impacts because they have forced downsizing. These claims clearly are contradictory, since CAFE standards causing little fuel economy benefit would have caused little downsizing. Indeed, most downsizing over the past decade and a half occurred in the first half of the period, when oil prices were both rising and uncertain and CAFE standards arguably may *not* have been the primary cause of fuel economy improvements. During the latter half of the period (1980-88), when oil prices were falling and the only clear motivator for increased fuel economy was the standards, little downsizing occurred—new car fleet fuel economy improved 20 percent while fleet average vehicle weight remained essentially constant.

Fifth, although NHTSA has claimed in testimony to Congress[45] that their NCAP crash tests show that smaller cars fare less well than larger cars in barrier collisions, NHTSA's own examination of the crash-test data, *weighted to account for difference in vehicle sales*, shows virtually *no* differences in occupant danger across weight classes.[46] This effect occurs both because poorer-performing vehicles have lower sales volumes and because many of the poorer-performing small cars are earlier models gradually being eliminated from the fleet.[47] In OTA's view, one credible interpretation of this effect is that small cars are less forgiving of poor design, but there is little difference in barrier-crash protection among *well-designed* small and large cars.

We conclude that potential safety effects of fuel economy regulation will most likely be a concern if sharp increases in CAFE are required over a period too short to allow substantial vehicle redesign—forcing manufacturers to try to sell a higher percentage of small cars of current design. In our view, significant improvements in CAFE should be possible over the longer term—by 2001, for example—without compromising safety. Over this time period, there are opportunities to improve CAFE without downsizing, and there also are opportunities to redesign smaller cars to avoid some safety problems currently associated with them. However, the *potential* for safety problems will still exist if automakers emphasize downsizing over technological options for achieving higher fuel economy and if they do not focus on solving problems such as the apparent increased rollover propensity of small cars of current design.

As a final point, we note that any safety concerns associated with new CAFE regulations will be relevant to *any* incentives to improve fuel economy, including gasoline taxes, gas guzzler or sipper taxes and rebates, and even simply higher oil prices, though compared to regulations, economic incentives allow automakers more latitude to make clearer tradeoffs based on consumer concerns. Consequently, if the United States desires to save gasoline through improved fuel efficiency, it needs to face the safety issue regardless of the energy conservation policy chosen.

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[45] NHTSA Car Size Summary.

[46] Hackney et al., 1989, op. cit., p. 5.

[47] Ibid.

FUEL SAVINGS OF S. 279

The magnitude of fuel savings likely from a new fuel economy standard is both a critical component of the decision calculus for the policy debate about standards and a source of great controversy because of large differences in estimates prepared by opposing interests. The source of these differences is the set of assumptions associated with each estimate. Critical assumptions affecting the magnitude of estimated savings include:

1. *Fuel economy values without new standards.* Alternative assumptions about the fuel economy of the new car fleet *in the absence of new standards* will play a critical role in estimating fuel savings associated with new standards. Factors affecting future fleet fuel economy include future oil prices and price expectations, fuel availability, consumer preferences for vehicle size and power, new safety and emissions standards, and progress in technology development. The span of credible assumptions about future fuel economy is likely to be quite wide, especially for the late 1990s and beyond.
2. *Use of alternative fuel credits.* Manufacturers can claim up to 1.2 mpg in CAFE credits by producing vehicles capable of using alternative fuels. In other words, using such credits, automakers can satisfy fuel economy standards while attaining about 1 mpg less in *actual* fuel economy. Assuming that automakers *would* make full use of credits if stringent new standards were passed—highly likely, in OTA's view—the validity of reducing the estimated fuel savings by the fuel "lost" because of the lower actual fleet fuel economy hinges on the likelihood of the credits being captured *in the absence of* the new standards. If alternative fueled vehicles would have been produced by the automakers solely because of the Clean Air Act requirements, with or without new fuel economy standards, then it is correct to subtract the "lost" fuel. If, on the other hand, it is the new fuel economy standards themselves that would provide the primary incentive for the vehicle production, then the standards should be given credit for any fuel savings associated with the alternative fuel use. It is worth noting that a high baseline value for fleet fuel economy implies that the credits will be worthless to the automakers, since they should all be well above the existing 27.5 mpg standard.
3. *Magnitude of a "rebound" in driving.* Because the magnitude of driving is at least partly a function of driving costs, an increase in fuel economy, by reducing "per mile" costs, may stimulate more driving and thus reduce the savings associated with the increased fuel economy. The magnitude of a "rebound" effect is controversial because it is estimated using historical driving trends that were influenced by a variety of factors aside from fuel costs, and many of these factors have changed over time. We would guess that a reasonable estimate for a likely rebound would be about 10 percent—in other words, for each 10 percent decrease in fuel consumed per mile, the vehicle is driven 1 percent more, and 10 percent of the expected fuel savings from higher fuel economy is lost to increased driving.
4. *Magnitude of vmt growth.* Over the period during which new fuel economy standards will take effect, small differences in the growth rate of vehicle miles traveled (vmt) can make a significant difference in the fuel savings estimated to occur from a new standard. As discussed in Chapter 4, actual vmt growth rates over the past few decades have been much higher than the future growth rates projected by the Energy Information Administration and others, and the credible range of future rates is fairly broad, perhaps from 1 to 3 percent per year. Even with no rebound effect (a large rebound would tend to exaggerate the effect of differences in the underlying vmt growth rate), the range in vmt growth rates can yield very large differences in calculated fuel savings. For example, in the year 2010 the estimated fuel savings from achieving the S. 279 standards

vary by 1.3 mmbd as the assumed vmt growth rate changes from 1 to 3 percent.[48]

5. *Effects of new standards on vehicle sales.* Some opponents of new fuel economy standards have argued that stringent standards will have the effect of slowing vehicle sales (because of higher vehicle prices and reduced customer satisfaction with smaller, slower, less luxurious cars), reducing vehicle turnover and the positive effect this has on fleet fuel economy. Others consider the likelihood of a sales slowdown large enough to affect fleet fuel economy in a significant manner to be very small. Clearly, an effect on turnover is theoretically possible, and would be likely if policymakers were to miscalculate and set a standard beyond automakers' technical capabilities.

There have been a number of different estimates of the effects of S.279, Senator Bryan's fuel economy legislative proposal. The Findings of the proposed bill state that attainment of the 20 percent (1996)/40 percent (2001) improvements in fuel economy levels will save 2.5 mmbd by 2005.[49] In contrast, the Department of Energy has estimated the fuel savings of S.279 to be about 0.5 mmbd in 2001 and about 1 mmbd by 2010.[50] Finally, the Congressional Budget Office (CBO) has estimated the fuel savings under three scenarios, with the base-case scenario having savings of 0.88 mmbd by 2006 and 1.21 mmbd by 2010[51] CBO's full range of estimates is 0.45 to 1.42 mmbd by 2006 and 0.59 to 1.82 mmbd by 2010.[52]

The differences among the above estimates can be readily understood by examining their assumptions. For example, ACEEE's calculations for Senator Bryan assume that fuel economy levels will remain unchanged from today's in the absence of new standards, i.e., about 28.5 mpg for cars and about 21 mpg for light trucks. The Department of Energy has assumed that, without new standards, new vehicle fleet fuel economy will rise to about 33 mpg for cars and 24 mpg for light trucks by 2001 and remain at that level thereafter.[53] This difference in baseline mpg assumptions is the most important factor in accounting for the difference between the DOE and ACEEE estimates. The DOE assumption is in line with EEA's "product plan" estimates for 2001 with higher oil prices and optimistic assumptions about the performance of fuel economy technologies. In fact, DOE's baseline oil prices are $29/barrel (1990$) in 2000 and $39/barrel in 2010—relatively high values. ACEEE's assumptions of "frozen" new car fuel economy assume continued low oil prices and a continuation of consumer preferences for more horsepower, larger vehicles, and more luxury options. They clearly are technologically pessimistic, and we believe that new car fleet fuel economy is unlikely to stay this low. CBO has chosen baseline mpg values of 30 mpg (range 28.5 to 33.0 mpg) for 2001, which appears more realistic as a midline estimate, though we believe even this value to be somewhat pessimistic.

For other factors, DOE has consistently chosen assumptions that would tend to yield lower estimated fuel savings than ACEEE. For example, DOE assumes that the automakers will capture alternative fuel credits with or without new fuel economy standards, and thus register an official fuel economy value about 1 mpg less than *actual* fuel economy. The ACEEE does not consider credits in its calculation, apparently assuming that automakers are unlikely to build many vehicles without the incentive of new standards. With the new California and Clean Air Act requirements for alternative fuels, the DOE position may be more realistic.

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[48] Assuming that the baseline (no new standards) case has an unchanging new car fleet fuel economy of 28 mpg, using a simplified model with 15 year vintaging (i.e., cars older than 15 years are retired, all other vintages assumed to drive the same amount)

[49] S.279, reported Apr. 25, 1991, sec. 2 (Findings)(15). This value was derived by J. DeCicco of ACEEE (J. DeCicco, Technical Memorandum of Mar. 19, 1991, "Sensitivity Analysis of Oil Savings Projected for New CAFE Standards," American Council for an Energy-Efficient Economy, Washington, DC).

[50] Letter of June 5, 1991, A.E. Haspel, Director, Office of Economic Analysis, DOE, to R. Friedman, Office of Technology Assessment, Attachment: Summary of DOE Bryan CAFE bill analysis.

[51] R.D. Farmer, Natural Resources and Commerce Division, Congressional Budget Office, Staff Memorandum, "Fuel Savings from Alternative Proposed Standards for Corporate Average Fuel Economy," June 1991.

[52] Ibid.

[53] There has been confusion about DOE's baseline assumptions, and some analysts have concluded that DOE assumed that fleet fuel economy would continue to grow after 2001 in the absence of standards. The assumption of constant new car fleet fuel economy after 2001 was confirmed by Barry McNutt, DOE Office of Policy and Planning, personal communication, Aug. 16, 1991.

Similarly, DOE assumes a 20 percent rebound from lower fuel costs, whereas ACEEE ignores any potential for a driving rebound. In OTA's view, it seems realistic to assume that a rebound will occur, though we are skeptical that the effect will be as large as DOE assumes. As noted, we would choose 10 percent as a better estimate of the probable effect.

Finally, DOE has assumed a lower vmt growth rate than ACEEE, resulting in an estimated year 2010 vmt that is about 20 percent lower than that estimated by Senator Bryan.[54] This accounts for about 10 percent of the difference between the two estimates.[55]

OTA concludes that the DOE baseline estimate of 1 mmbd fuel savings from S.279 by 2010 is analytically correct but very conservative. Although none of its assumptions are extreme, virtually *all* push the final result towards a low value.[56] In our view, the likelihood of such uniformity is small, although much less improbable if oil prices follow their assumed (upwards) path. For example, most analysts believe that future fuel economy levels will be very sensitive to oil prices (and price expectations). The auto fuel economy levels assumed in the Energy Information Administration's Annual Energy Outlook 1991[57] exhibit this sensitivity—the assumed year 2000 new car fuel economy is 34.7 mpg with oil prices at $31.10/bbl (1990$) that year, and 31.4 mpg with oil prices at $20.10/bbl.

In contrast to the DOE estimate, the Bryan/ACEEE estimate of 2.5 mmbd by 2005 appears very optimistic because it discounts the potential for a driving "rebound" and, more importantly, accepts unusually pessimistic assumptions about likely fuel economy improvements in the absence of new standards.

Although the range of potential fuel savings from S. 279 is wide, OTA believes that the "most likely" value for year 2010 savings lies between 1.5 mmbd and 2 mmbd. For a 10 percent rebound effect, 2 percent/year vmt growth rate, baseline fuel economy of 32.9 mpg in 2001 (frozen for the next decade), and no accounting for alternative fuel vehicles, we calculate the fuel savings to be 1.64 mmbd in 2010.[58] Although the 32.9 mpg baseline (no new standards) value is optimistic unless oil prices rise substantially, it is also likely that the automakers will gain some alternative fuel credits in the baseline; these two factors will tend to cancel one another. Figure 9-4 displays the projected U.S. oil consumption over time for the baseline and S.279 cases discussed above. The figure also displays the consumption projected under OTA's "regulatory pressure" scenario for new car fuel economy.

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[54] Letter of June 5, 1991, A.E. Haspel, Director, Office of Economic Analysis, DOE, op. cit.

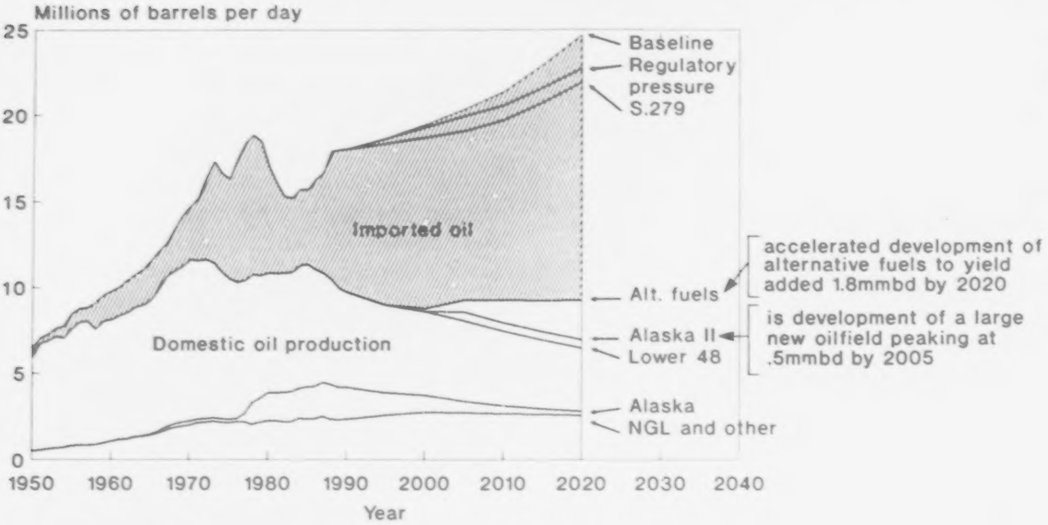
[55] Ibid.

[56] This may not be true for later years. The DOE assumption that post 2001 fleet fuel economy levels will not continue to improve may be overly pessimistic. Any DOE estimates of savings in years past 2010 may shift from conservative to optimistic because of this flat baseline fuel economy assumption.

[57] Energy Information Administration, *Annual Energy Outlook 1991*, DOE/EIA-0383(91), March 1991.

[58] Other assumptions: 15 year vintaging, fuel economy assumed to keep rising after 2001 (in regulated case) to 50 mpg by 2020.

Figure 9-4—U.S. Oil Consumption Under Alternate Scenarios—With or Without Higher Fuel Economy Standards



ASSUMPTIONS:
1 Baseline assumes no new policy measures, new car fuel economy reaches 32.9 mpg in 2001 and stays constant thereafter
2 S.279 assumes new car fuel economy reaches 40 mpg by 2001 and 50 mpg by 2020
3 Regulatory pressure assumes new car fuel economy reaches 35 mpg by 2001 and 45 mpg by 2020

SOURCE: Office of Technology Assessment, 1991

Chapter 10

Regulation of Light-Truck Fuel Economy

Because light trucks make up a rapidly growing proportion of the passenger vehicle fleet, and consumers can readily find transportation alternatives to new cars in the light-duty truck fleet, fuel economy regulations must address light-truck fuel economy to assure an effective reduction in total fuel use. Proposed legislation generally recognizes this necessity and sets standards for trucks similar to those for automobiles. For example, S.279 proposes that light trucks attain the same 20- and 40-percent fuel economy increases (by 1996 and 2001, respectively) as automobiles.

Although light trucks are commonly used for passenger travel, they must remain capable of performing tasks seldom expected of automobiles. Dissimilarities between light trucks and automobiles create differences in the fuel economy improvement potential of these vehicle classes, as well as differences in the way the two classes might best be treated using standards based on vehicle capability (such as interior volume). Because of diversity in capability and purpose among classes of light trucks and among truck fleets of various manufacturers, a uniform-percentage-increase approach to fuel economy appears problematic.

FUEL ECONOMY POTENTIAL

Light-duty-trucks include those vehicles classified as pickups, vans, and utility vehicles with a gross vehicle weight under 8,500 lb. These trucks have become an important source of fuel consumption as their sales now constitute 30 percent of light-duty (cars plus light trucks) vehicle sales. Although their fuel economy potential has not been analyzed as comprehensively as for cars, there are significant similarities between technologies available to improve car fuel economy and those available to improve light trucks. This is because most light trucks utilize drivetrains derived from car drivetrains, and vehicle structure-related improvements can follow similar trends. However, some limitations prevent light-truck fuel economy from improving at the same rate forecast for cars.

First, load carrying requirements for light trucks are significantly higher than for all but the largest cars. With a much larger proportion of total loaded weight being payload, there is less opportunity for "flowthrough" weight reductions from initial weight reductions due to engine downsizing or use of advanced materials.

In addition, load carrying requirements of trucks do not favor front-wheel drive, because loading a truck decreases traction with a front-wheel-drive configuration, whereas a rear-wheel-drive truck achieves increased traction when carrying a heavy load. Generally, front-wheel drive is used only in small vans.

Second, aerodynamic drag reduction is necessarily limited by the open cargo bed for pickups and by the large ground clearance needed for utility vehicles. However, because of previous lack of attention, there is room for significant improvements in truck aerodynamic design even within these limitations.

Third, the benefits of a four-valve engine are smaller for trucks than for cars because the low rpm torque tradeoff places greater limits on how much the engine can be downsized. Moreover, high rpm characteristics of the four-valve are wasted to some degree on a truck, making it less attractive from a marketing standpoint.

Fourth, trucks and cars currently do not have the same safety and emission requirements, but these are converging. As a result, future light-truck fuel economy penalties associated with safety and emissions standards will be proportionately larger than for cars.

These limitations are partially offset by the generally less-advanced technology applied to most light trucks, including their inferior aerodynamic design, less sophisticated engines and transmissions, and more limited use of weight-saving materials and design. This lack of technological sophistication allows more "headroom" for further advancement in some areas. Also, conflicting performance requirements for passenger use and heavy hauling can yield opportunities for powertrain components that can handle both load regimes efficiently (e.g., multispeed transmissions with load-sensitive final drive ratios).

A preliminary estimate by EEA suggests that a maximum technology scenario for light-duty trucks will have a fuel economy increase potential 5-to 7-percent lower than the increase calculated for cars. In 1988, domestic trucks averaged 20.2 mpg, and a "maximum technology" scenario for 2001 suggests domestic trucks can attain 26.0 mpg. At the same time, it should be noted that this forecast excludes diesels, which could be as popular in the 6,000- to 8,500-lb range of trucks as they are in the 8,500- to 10,000-lb range currently not covered by CAFE legislation. Use of diesel engines could raise the 26.0 mpg forecast by 1 to 2 mpg if diesel market penetration increases to 10 or 20 percent.

DEFINING AN EFFECTIVE FORMAT FOR A LIGHT-TRUCK FUEL ECONOMY STANDARD

The debate on CAFE suggests the widespread belief that current uniform mpg standards penalizes many manufacturers while rewarding others. Current CAFE standards for light trucks are set for two-wheel drive and four-wheel-drive trucks separately, although manufacturers have the option of meeting a combined standard. In 1993, separate standards will be eliminated and manufacturers will have to meet a combined standard. Some observers have suggested that light trucks should be integrated into any new schemes proposed for cars, since consumers utilize these vehicle types interchangeably. Among new schemes proposed for cars is an interior-volume-based standard. OTA concludes that a volume average fuel economy (VAFE) or similar approach can work well for autos, but VAFE does not allow light trucks to be integrated into the calculation in a straightforward way.

Since light-duty trucks cover a variety of vehicle types, no single measure of consumer attributes such as interior volume provides a useful index for future fuel economy regulation. Light-duty trucks can be subdivided by body style into pickups, vans, and utility vehicles; these three main types of light trucks offer different consumer attributes.

Of the three, vans used for carrying passengers (as opposed to cargo vans) are very similar to passenger cars. Interior volume may be a good measure of consumer attributes for passenger vans. The relatively high roof of a van exaggerates the useful interior volume for passengers, but (possibly) not for luggage. Hence a "corrected" or reduced passenger volume index can allow passenger vans to be integrated into the VAFE calculation for cars.

Utility vehicles also have passenger-car-like interiors, but most are four-wheel-drive vehicles suitable for rough terrain use. Four-wheel drive imposes a weight penalty as well as an increased drivetrain friction penalty. Moreover, the ability to traverse rough terrain requires good ground clearance, resulting in poor aerodynamic drag coefficients. All of these factors cause a utility vehicle of the same interior size as a passenger car to have much poorer fuel economy. Such vehicles can be integrated into a VAFE calculation for cars if they are provided an mpg credit for rough-terrain capability. The credit must be on the order of 15 to 20 percent for integration into a passenger-car VAFE calculation.

Pickup trucks and cargo vans are purchased ostensibly for cargo carrying capability rather than passenger room. Of course many purchasers simply like the image of a pickup truck and rarely utilize its load carrying capacity. Surveys by DOT in the late 1970s and early 1980s found that weight capacity was rarely a limiting factor, but cargo size often was (i.e. typical loads have large volumes but not high weights). Hence, cargo floor area or total cargo volume (for vans) is an important attribute, but weight carrying capacity may be a factor if it is too low. Many customers use their trucks to tow a trailer or boat, and towing capacity has been suggested as an important attribute to many customers. The ability to carry a heavy load is related to the towing capacity as well, so that there is correlation between these two attributes. One index of truck attributes may be cargo area x load capacity, with some measure like "square foot-tons" used to regulate fuel economy rather than cubic feet of space. Of course payload tons alone can be utilized, but this does not capture the size requirement. For example, many compact trucks have the same payload capacity as the basic full-size pickup truck (1,200 to 1,400 lb), but offer a small cargo bed making it difficult to carry construction materials. Hence, a "square foot-tons" measure appears superior to a payload-only measure (such as "tons") as an attribute index for pickups and cargo vans.

Appendix A

EEA's Methodology to Calculate Fuel Economy Benefits of the Use of Multiple Technologies

OVERVIEW

Fuel economy behavior of a vehicle is dependent not only on individual technologies employed, but also on how they are applied and, to some extent, on what technologies are present simultaneously. In the EEA methodology, the fuel economy benefit due to technology changes in a given automobile is always calculated holding vehicle size, as measured by interior volume, and vehicle performance constant. The second term is more complex to define; but each technology that affects horsepower or torque of the engine or weight of the vehicle is examined in detail, and appropriate tradeoffs to measure fuel economy benefit on a constant performance basis are identified and defined.

Individual technology benefits are defined relative to a base technology and are expressed as percent benefits to fuel economy. If the technology represents a change to a continuous variable (e.g., weight), the impact of a specific percent change in the variable (e.g., 10) on fuel economy is estimated. If the technology represents a discrete technology, the percent benefit for that technology is defined relative to replacing a base technology (e.g., four-valve engine replacing a two-valve engine), holding the size and performance parameters constant. Table A-1 provides a list of technologies discussed in this report and the

Table A-1 — Technology Definitions

Technology	Definition
Front-wheel Drive	Benefits include weight reduction and engine size reduction starting from a late 1970's rearwheel drive vintage design
Drag Reduction I	Based on C_D decreasing from 0.375 in 1987 to 0.335 in 1995, on average[1]
Drag Reduction II	Based on C_D decreasing from 0.335 to 0.30 in 2001, on average[1]
Torque Converter Lock-up	Lock-up in gear 2-3-4 compared to open converter
Four-speed Auto Transmission	Three-speed automatic transmission at same performance level
Electronic Transmission Control	Over hydraulic system, with electronic control of shift schedule and lock-up of torque converter
Accessory Improvements	Improvements to power steering pump, alternator, and water pump over 1987 baseline
Lubricants (5W-30)	Over 10W-40 oil
Overhead Camshaft	OHV engine of 44-45 bhp/liter replaced by 0HC engine of 50-52 bhp/liter but with smaller displacement for constant performance
Roller Cam Followers	Over sliding contact follower
Low-friction Pistons/Rings	Over 1987 base (except for select engines already incorporating improvement)
Throttle-body Fuel Injection	Over carburetor (includes air pump elimination effect)
Multipoint Fuel Injection	Over carburetor; includes effect of tuned intake manifold, sequential injection and reduced axle ratio for constant performance
Four-Valve Engine (OHC/DOHC)	Over two-valve 0HC engine of equal performance; includes effect of displacement reduction and compression ratio increase from 9.0 to 10.0
Tires	Over 1987 tires, due to improved construction
Intake Valve Control	Lift and phase control for intake valves; includes effect of engine downsizing to maintain constant performance
Advanced Friction Reduction	Includes composite connecting rod, titanium valve springs, light-weight reciprocating components

[1] To exploit the benefits of drag reduction, the top gear must have a lower (numerical) ratio to account for the reduced aerodynamic horsepower requirement.

baseline technology against which benefits are measured.

Of course, no technology will be used in isolation, and synergistic and non-additive constraints must be recognized: engineering analysis is used to identify technologies that simultaneously contribute to reduction of the same source of energy loss and quantify the loss of total benefit when both technologies are used in the same vehicle; and the sum of market penetration of two non-additive technologies is not allowed to exceed 100 percent, since both technologies cannot be present in the same car.

The computational methodology uses a linear form of the exact engineering equation. Although the method is an approximation to simplify calculations, it yields results that have historically been accurate to 0.2 mpg. In projecting a maximum technology boundary case for the post-2000 timeframe, it is believed that these approximations could cause larger errors and a more rigorous engineering model is required. The current model is described below.

ENGINEERING MODEL

The model follows the work of Sovran (1,2) who produced a detailed analysis of tractive energy requirements on the EPA fuel economy test schedule (i.e., the city cycle and the highway cycle). Each driving cycle specifies speed as a function of time. The force required to move the vehicle over the driving cycle is easily derived from Newton's laws of motion:

$$F = M(dv/dt) + R + D$$

where F is the force required

M	is the vehicle mass
dv/dt	is the acceleration rate
R	is the tire rolling resistance
D	is the drag force

From the knowledge of physics, it can be shown that

$$F = M(dv/dt) + gMC_RV + C_D\, A\rho V^2/2 \qquad (1)$$

where C_R is the tire rolling resistance coefficient

C_D	is the drag coefficient
g and ρ	are the gravitational acceleration and air density respectively
V	is the vehicle speed
A	is the vehicle cross-sectional area

Over the fuel economy test, V is specified as V(t), and the energy required E is the integral of

$$F\,dS = F\,V\,dt$$

where S is the distance traveled.

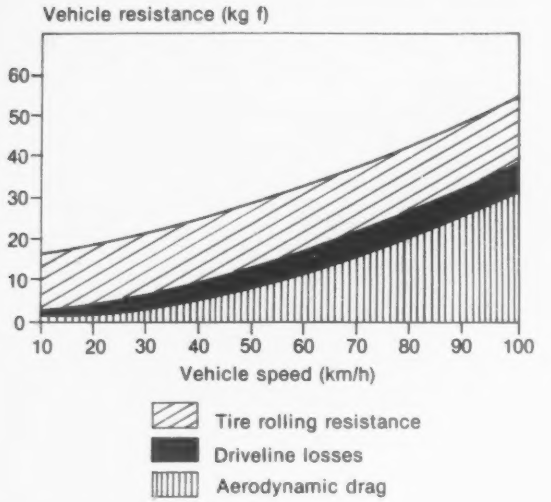
In the car, energy is provided only when F is greater than zero, while energy during deceleration is simply lost to the brakes. Taking these factors into account, Sovran and Bohn (2) showed that energy per unit distance

$$E/S = \alpha\, MC_R + \beta\, C_DA + \delta M \qquad (2)$$

where α, β, and δ are constants virtually independent of vehicle characteristics, but differ for city and highway cycles. In essence, each term represents one component of the total force: the first term represents E_R the energy to overcome tire rolling resistance, the second represents E_A the energy to overcome aerodynamic drag, and the third represents E_K kinetic energy of acceleration. In the absence of acceleration (during steady speeds) E_K is zero. Figure A-1 shows the drag and the rolling resistance forces for a typical car at steady cruise, as well as the driveline loss described below.

Sovran (1) also related tractive energy to fuel consumption by adding the work required to drive accessories and the energy wasted by the engine during idle and braking. He defined the average engine brake specific fuel consumption

Figure A-1—Vehicle Resistance in Coastdown Test



SOURCE: Energy & Environmental Analysis, Inc., 1991.

over the test cycle as bsfc, and derived the following equation for the total fuel consumption over the test cycle:

$$FC = \text{bsfc}/\eta_d \times [E_R + E_A + E_K] + \text{bsfc}\ E_{AC} + G_i\,(t_i + t_b) \quad (3)$$

where η_d is the drivetrain efficiency

E_{AC}	is the accessory energy consumption
G_i	is the idle fuel consumption rate
t_i,t_b	is the time at idle and braking in the test cycle

The above equation shows that reductions in rolling resistance, mass, drag and accessory energy consumption, and idle fuel consumption cause additive reductions in fuel consumption.

The engine output energy is supplied to match the tractive energy requirements. If total energy required is defined as

$$E = 1/\eta_d \times [E_A + E_R + E_K] + E_{AC} \quad (4)$$

then $E = BHP \times t$

where BHP is engine power output.

Engine output power can be further decomposed to provide explicit recognition of engine internal losses. There are no conventions regarding the nomenclature of such losses. In general, the engine has two types of losses: one arising from the thermodynamic efficiency of combustion and heat recovery, and the second due to friction, both mechanical and aerodynamic. Aerodynamic friction is more usually referred to as pumping loss.[1] A third component that is sometimes excluded from the engine efficiency equation is the power required to drive some internal accessories such as the oil pump and the distributor. Items such as the water pump, alternator, and fan are usually (though not always) classified under accessory power requirements. In this analysis, power for all accessories—both internal and external—is classified under accessory power requirements, and the following relationship holds:

$$BHP = IHP\,(1 - P - F_R) \quad (5)$$

Where IHP is power generated by the positive pressure in the cylinder

P	is the pumping-loss fraction
F_R	is the mechanical-friction-loss fraction

Since fuel consumption can be written as

$$FC = \overline{\text{bsfc}} \times BHP \times t = \overline{\text{isfc}} \times IHP \times t$$

where isfc is the indicated specific fuel consumption, that is, the fuel consumed per unit of horsepower prior to engine losses:

$$\overline{\text{bsfc}} = \overline{\text{isfc}}\,/\,(1 - P - F_R) \quad (6)$$

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[1] **We distinguish between throttling loss and pumping loss, using the latter term to include both throttling loss and frictional losses in the exhaust and intake system.**

Substituting equation (6) into (3) we obtain

$$FC = \overline{isfc}/[\eta_d(1-P-F_R)] \times [E_R + E_A + E_K + \eta_d E_{AC}] + G_i [t_i + t_b] \quad (7)$$

The isfc is principally a function of combustion chamber design and compression ratio of the engine, and to a lesser degree, the air/fuel ratio. Since nearly all cars operate at stoichiometry, the air/fuel ratio is currently not a factor but could become one if "lean-burn" concepts are utilized.

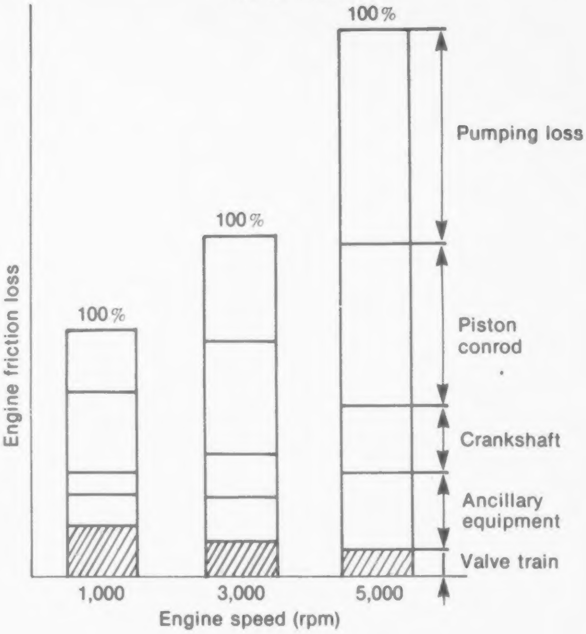
Pumping losses are dependent principally on the relative load of the engine over the cycle. The larger the engine for a given car weight, the lower the load factor and the higher the pumping loss due to throttling. Pumping losses are also incurred in the intake and exhaust manifolds and valve orifice. Use of tuned intake and exhaust manifolds and a greater valve area (e.g., by utilizing four valves/cylinder) reduce pumping losses. Losses other than throttling loss are not unimportant in the contribution to overall pumping loss.

Engine mechanical friction is associated with the valve train losses, piston and connecting rod friction, as well as the crankshaft friction. At low rpm, valve train friction is quite a large percentage of total friction, but decreases at higher rpm, while piston and connecting rod friction increases rapidly with increasing rpm. Total engine friction increases nonlinearly with engine rpm.

Idle fuel consumption is also affected by changes in engine parameters. At idle, all fuel energy goes into driving the accessories and overcoming pumping and friction loss, since there is no output energy requirement. Hence, decreases in pumping loss or mechanical friction result in a much larger percentage reduction in fuel consumption at idle than at load.

Mitsubishi provided data on general components of engine friction (figure A-2). The pumping loss shown here is due to internal airflow and not due to throttling. At closed throttle, idle pumping loss is approximately equal to frictional loss.

Figure A-2—Proportion of Engine Friction Due to Valve Train



SOURCE: Energy & Environmental Analysis, Inc., 1991.

Equation (7) also shows the general structure of the calculation procedure. A simple differentiation of (7) yields:

$$\frac{dFC}{FC} = \frac{d(\overline{isfc})}{isfc} + \frac{P}{1-P-F_r} \times \frac{dP}{P} + \frac{F_r}{1-P-F_r} \times \frac{dF_r}{F_r} + \frac{E_A}{E_A + E_R + E_k + \eta_d E_{AC} E_A} \times \frac{dE_A}{E_A} + \ldots + \ldots \quad (8)$$

where each derivative is expressed as a percentage change. Thus, a one-percent change in isfc translates into a one-percent change in fuel economy, but a one-percent change in pumping loss must be weighted by the fraction that pumping loss is of total output energy. Similarly, aerodynamic tractive energy change must be weighted by the fraction that aerodynamic energy loss is of total tractive energy.

Two observations are required at this point. First, equation (8) assumes the vehicle can be reoptimized for any change, so that engine variables are not affected by tractive energy requirements. Sovran points out this is not always possible. For example, aerodynamic losses are near zero at low speed but high at high speed. Hence, an engine cannot be simply downsized as aerodynamic loss is reduced, since the smaller engine will not have enough power at low speed. A higher gear must be added along with engine downsizing to achieve a correct compromise. In theory, it is possible to reoptimize the entire drivetrain, but in practice compromises cause significant losses in fuel economy from the attainable maximum. In the long run, as for 2010, some factors can indeed be optimized to yield the full predicted value, while other factors cannot. For example, it appears that predicted fuel savings related to friction-loss reduction are unlikely to be obtained as the engine cannot be downsized to the point where low-speed torque is compromised. On the other hand, rolling resistance decreases may provide the predicted fuel savings, as their effect is felt uniformly throughout the speed range.

CALCULATION PROCEDURE

Methods to increase fuel economy (reduce fuel consumption) must rely on reduction of energy contributed by each of the terms shown in equation (7). Equation (8) is useful if the change in factors is small, but not applicable for large changes. Focusing on the terms in equation (7), it is easily seen that fuel consumption is decreased by:

- decreasing friction and pumping loss;
- decreasing weight;
- decreasing drag;
- decreasing rolling resistance;
- decreasing accessory power consumption; or
- decreasing idle fuel consumption.

Of course, a given technology can act on more than one of these factors simultaneously. Table A-2 shows the relationships between individual technologies and the terms listed in equation (7). Drivetrain efficiency, η_d, is not the major factor in the benefits associated with multispeed transmissions; rather, the reduction in pumping and frictional losses are the biggest factor. It should also be noted that all engine improvements affect idle fuel consumption, so that idle consumption can be assumed to follow the same trends as bsfc, allowing equation (8) to be rewritten as

Table A-2—Technology/Energy Use Relationship

	isfc	P	F_r	E_A	E_R	E_K	E_{AC}	G_I	η_d
Weight reduction					!	!			
Drag reduction				!					
Four-speed automatic		!	!						!
TCLU									!
Electronic trans control		!	!						
Accessory improvements							!		
Tire improvement					!				
5W-30 oil			!						
Overhead cam	!	!	!					!	
Roller cam followers			!					!	
Low-friction piston/rings			!					!	
Fuel injection	!	!						!	
Four-valves/cylinder	!	!						!	
Intake valve control		!							!
Five-speed automatic		!	!						
Electric power steering							!		

$$FC = \overline{isfc} \times [E_R + E_A + E_K + \eta_d(E_{AC} + E_I)]/\{\eta_d\,[1 - P - F_R]\} \quad (9)$$

where E_I is an "equivalent" energy at idle to drive the accessories and torque converter. E_I is simply a mathematical artifact to make the analysis simpler for forecasting.

The relationship between fuel consumption and vehicle variables can be derived from equation (7) in exact terms if the coefficients are evaluated for the urban and highway driving cycles. In fact, Sovran utilized a detailed evaluation of these cycles to derive the sensitivity of fuel consumption to vehicle weight, aerodynamic drag, and tire rolling resistance coefficient. The general characteristics of the two cycles are shown in table A-3. One striking factor is that nearly 41 percent of urban time is spent in deceleration or at idle. In comparison, less than 10 percent of the time on the highway cycle is spent in braking or at idle. This difference, coupled with the different speeds and average acceleration rates in each cycle, leads to substantially different sensitivities between the two cycles.

In order to evaluate sensitivity of fuel consumption to changes in vehicle parameters, information is required on fuel consumption at idle and braking as well as fuel consumed by driving accessory loads. Sovran utilized data on 1979-80 GM cars and found that idle and braking fuel consumption was proportional to engine size. As an approximation, he assumed idle plus braking consumption to be a constant percentage of total fuel consumed and estimated this percentage at 16 for the urban and 2 for the highway cycle. He utilized a similar assumption for the accessory fuel consumption percentage, holding it constant at 10 and 9 respectively. This is equivalent to the approach in equation (9) where the term $[E_{AC} + E_I]$ bsfc is replaced by a constant percentage of FC. Utilizing these assumptions, he derived sensitivity coefficients that were dependent on the drag-to-mass ratio and the rolling resistance coefficient. Using typical values for the average 1988 car, with a mass of 1400 kg (3,100 lb), C_D of 0.37, frontal area of 1.9 m^2, and C_R of 0.01, the fuel consumption sensitivity coefficients are as follows:

α (for C_D) = 0.28

β (for Weight) = 0.54

δ (for C_R) = 0.24

Table A-3—Fuel Economy Cycle Characteristics

	Urban	Highway
Average speed (km/h)	38.4	77.60
Maximum speed (km/)h	91.5	96.80
Distance (km)	12.0	16.50
Time at idle (s)	249.0	3.00
Time of braking (s)	311.0	57.00
Total time for cycle (s)	1,373.0	765.00
Percent of time at idle and braking	40.8	7.84

The weight reduction sensitivity coefficient above does not incorporate the effect of engine downsizing, which reduces idle/braking fuel consumption proportionally. The coefficients assume that the engine and drivetrain are adjusted to provide constant bsfc (a factor which may not be realized in practice) but do not account for engine downsizing. Second, the constants are dependent to a certain extent on the assumptions for the fraction of fuel consumed at idle plus braking, and by accessory power demands (the smaller these fractions, the larger the sensitivity coefficients).

Table A-4 provides a summary of the values of sensitivity coefficients attained in actual practice as opposed to estimates derived purely from equation (8). In the application of these coefficients, it should be recognized that they can be

Table A-4—Estimated Fuel Consumption Sensitivity Coefficients (Percent reduction in fuel consumption per percent reduction in independent variable)

Variable	Fuel Consumption Sensitivity	Fuel Economy Sensitivity
Weight reduction	0.62[1] (0.54)	0.66
Drag reduction (C_D)	0.22	0.23
C_R reduction	0.23	0.24
Thermal efficiency	1.00	1.00
Pumping loss	0.23	0.24
Friction loss	0.23	0.24
Drivetrain efficiency	0.78	0.81
Accessory power	0.10	0.11

[1] 0.62 includes proportional reduction of displacement, 0.54 assumes constant displacement.

used only for modest variations for any variables involved.

When large reductions of any variable are likely to occur, the preferred form of analysis is to use equation (7) with a "slippage" factor to account for benefits that cannot be attained in actual practice for some variables of concern.

The methodology used to calculate the fuel economy benefit due to the application of any set of technologies to the automobile is as follows. First, the technology set is examined to identify which energy-use factors are affected and areas of overlap are examined for synergy. Second, the net reduction in each specific energy-use area is estimated and the benefits to fuel consumption calculated with equation (8). In general, synergies occur primarily in pumping loss reduction, with smaller synergies in the area of friction reduction.

FORECASTING METHODOLOGY

The theoretical concepts behind the forecast have been explained through the engineering equations. The exact method of forecasting fuel economy involves the following sequence of steps:

- defining a baseline;
- identifying available technology;
- adopting technology at the proper level of market penetration; and
- calculating fuel economy after adoption of technology.

The analysis can be performed at the model-specific level (such as Ford Escort or Chevrolet Caprice) or at a more aggregate market class level, where vehicles within a market class are very similar in size, performance, and option levels.

All the analyses begin by defining a baseline of vehicle technology and fuel economy derived from actual data. For example, the choice of the 1988 Ford Escort as the baseline requires identification of all vehicle characteristics such as weight, drag coefficient, engine size and power, types of transmissions, acceleration performance, type of fuel system, etc. as well as the actual EPA composite fuel economy rating for 1988. If the analysis is at a market class level, these characteristics are averaged across all models in the given year, and discrete technologies such as fourspeed automatic transmissions are described by their market share within the class.

Once baseline technologies are detailed, available technologies are identified along with the potential availability dates. In the short term, most technologies available for improvement are dictated by the product plan for a particular model, and these are tracked through articles in the trade press. For the longer term, EEA selects available technologies based on both product lifecycle of the model as well as technology readiness. Continuing with the Ford Escort as the example, its product lifecycle is eight to nine years and a new design was introduced in 1990. This implies that major changes can be made when the next model is introduced in 1998-99.

Technology readiness is based on EEA's determination of when a technology is likely to be broadly adopted in the marketplace. For example, we expected that four-valve-per-cylinder technology could be broadly adopted by domestic manufacturers in the 1991-98 timeframe, whereas five- valve-per-cylinder technology is unlikely to enter the mainstream until 2001. Such determinations are based on interviews with auto manufacturers and involves some subjective judgment. It is recognized that technology availability does not guarantee its introduction in the marketplace; this depends on the costs of a technology and its benefits. A simple model of technology adoption by the manufacturers is one where technology is adopted in a carline if the value of fuel saved over a specific period exceeds its first cost to the consumer. Analysis of historical data suggests a period of four years (typical of new-car ownership) for payback provides a good approximation of past manufacturer behavior, and we have utilized this to represent scenarios of business as usual or "product plan" scenarios. Other scenarios can be easily constructed to evaluate technology adoption based on fuel savings over a vehicle lifetime (10 or 12 years), or in total disregard of any cost-effectiveness criteria where all available technologies are adopted to the maximum extent possible. Table A-5 presents the estimated costs of the existing fuel economy technologies included in the forecasts.

Technology adoption is usually associated with a level of market penetration. For most technologies, it is an "all-or-nothing" decision at the carline level, since, for example, a given car will either have a new lowdrag body or it will not. Technology non-additivity must be accounted for so two technologies (such as manual and automatic transmissions) that cannot be present in the same car are not assumed to each have 100-percent market penetration. However, there are some technologies offered as options in a given model, where the consumer has a choice. Typically, these involve performance engines or engines using other fuels such as diesel engines. Evaluation of their market penetration is either developed by specific scenario assumptions, or else determined by trend analysis or results from consumer surveys if the object is to forecast fuel economy.

Table A-5—EEA's Estimates of Incremental Retail Price of Fuel Economy Technology (1988$)

Front Wheel Drive		240	
Drag Reduction	to CD = 0.33	32	
	to CD = 0.30	48	
4-Speed Automatic Transmission		225	
Torque Converter Lock-up		50	
Electronic Transmission Control		24	
Accessory Improvements		12	
OHC Engine:	4-cylinder	110	
	6-cylinder	160	
	8-cylinder	200	
4-valve heads:	4-cylinder	140	
	6-cylinder	180	
	8-cylinder	225	
Roller cams		4	per cylinder
Friction reduction I:	4-cylinder	30	
	6-cylinder	40	
	8-cylinder	50	
"Advanced Pushrod"		40	(6-cylinder)
Throttle Body Fuel Injection (over carburetor)		42	(one injector)
		70	(two injector)
Multipoint Fuel Injection (over throttle body)	4-cylinder	48	
	6-cylinder	64	
	8-cylinder	80	
Tire Improvements		12	(4 tires)
Oil (5W-30)		2	
5-speed Automatic (over 4-speed)		100	
Continuously Variable Transmission (over 4-speed auto)		100	
Advanced Friction Reduction		same as Friction Reduction I	
Tire Improvements (1995-2001)		18	
Intake Valve Control	4-cylinder	140	
	6-cylinder	200	

SOURCE: Energy & Environmental Analysis, Inc., 1991.

The calculation of fuel economy after technology adoption is relatively simple using the "linearized" method detailed earlier, but specific adjustments are made for synergistic effects between two technologies. The synergies are recognized through engineering analysis, as the operation of each technology is well understood and the source of its benefits is known (in terms of reduction of specific losses identified in the engineering equations). In brief, the model is

$$FC = FC_0 \left[1 + \Sigma\, m_i x_i + \Sigma\Sigma s_{ij}\, m_i m_j\right]$$

where FC_0 is the baseline fuel economy

m_i is the market penetration of the i^{th} technology

x_i is the percent fuel economy benefit of the i^{th} technology

s_{ij} is the synergistic effect between technology i and j on fuel economy

DATA SOURCES

The model of fuel economy shown above requires detailed estimates of the fuel economy effect of each technology, as well as estimation of non-additive and synergistic effects of each technology with other technologies. One factor aiding in the recognition of technology-specific fuel economy effects is the criteria utilized to select available technologies for 2001, which require that every technology be sold commercially in 1991 in at least one mass-produced car model. This, of course, makes it possible to scrutinize available models and their fuel economy to discern the effects of specific technologies.

In general, detailed estimates of technology characteristics are based on the following sources of information:

- data developed by the Department of Transportation (DOT) in the late 1970s and early 1980s;
- data submitted by manufacturers to DOT during the 1980s in response to new rulemaking on CAFE standards;
- data published in scientific journals or papers published by automotive engineering societies worldwide, or provided by auto manufacturers during interviews with EEA staff;
- data based on detailed vehicle-to-vehicle comparisons from available models; and
- engineering analysis concluded by EEA staff on the technologies.

Due to the maturity of the automotive engine, it is a relatively rare occurrence that data available for a given technology from different sources provide highly conflicting results when properly interpreted. Specifically, technology benefits are sensitive to how the technology is applied and the nature of the vehicle before and after technology application. As noted, any technology can be utilized to improve performance rather than fuel economy, and careful control of performance related variables is essential in making judgments about technology benefits. Another factor is the state of technology maturity; typically, a technology is not optimal at its introduction, but is developed more fully over a few years. These factors introduce uncertainties in car-to-car comparisons, and data from such comparisons are validated by data from other sources before technology characteristics are assigned.

Product plan information is often readily obtainable in trade publications. For example, recent issues of *Automotive News* have contained Ford product and engine plans (Sept. 10, 1990, and Dec. 10, 1990, respectively), Chrysler product plans (Oct. 1, 1990), and a variety of European product plans (July 8, 1991).

REFERENCES FOR APPENDIX A

1. G. Sovran and M.S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule," SAE Paper 810184, February 1981.
2. G. Sovran, "Tractive-Energy-Based Formulae for the Impact of Aerodynamics on Fuel Economy Over the EPA Driving Cycle," SAE Paper 830304.

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